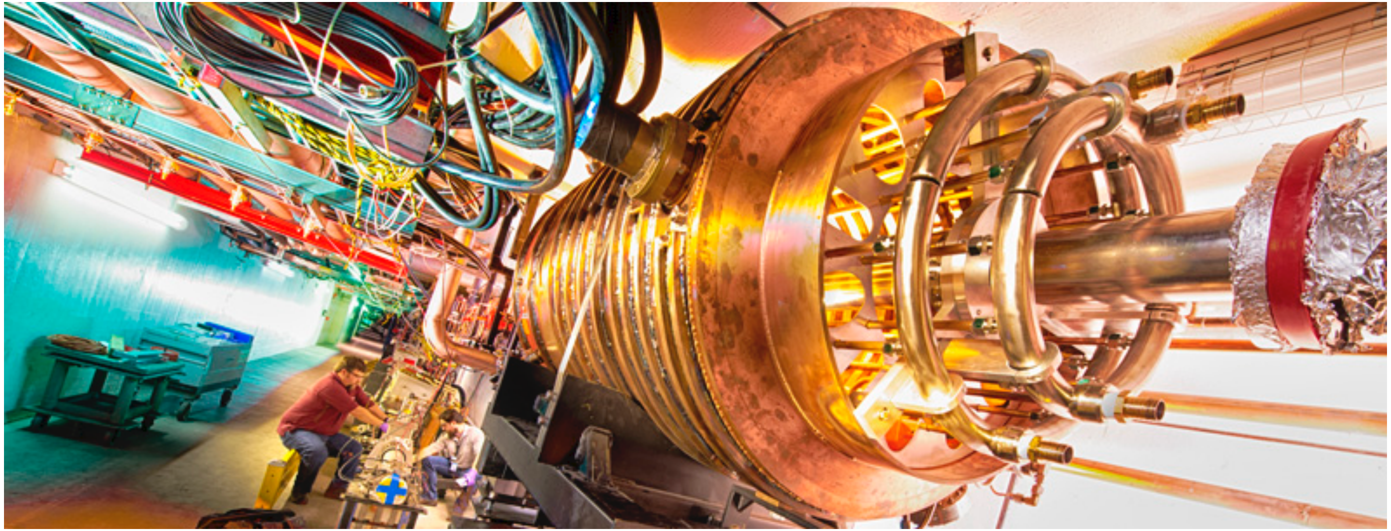

Accelerators for Neutrinos at Fermilab

Paul Derwent
Accelerator Division, RF Department
April 16 2020

About me

- PhD University of Chicago, 1990
  - CDF Collaboration: W and Z cross section measurements
- Post-Doc University of Michigan
  - CDF Silicon Vertex detector: radiation protection, tracking
  - Correlated μ – b quark production cross sections
- Scientist Accelerator Division since 1995
  - Pbar: Stochastic Stacking
  - Run Coordinator, 2001 Run II Collider startup
  - Joined Accelerator Upgrades for NOvA 2006
    - Associate Project for Accelerator and NuMI Upgrades (ANU)
    - Member of the NOvA collaboration
  - PIP-II, Operations
  - Currently in the RF department

Neutrinos have been a focus at Fermilab since the beginning

- The first approved experiment
  - E1A, April 15 1970
    - 1200 hours, with completion of the experiment defined as 20,000 events with 2×10^{17} protons on a horn focused beam

- In early 1971, Wilson told the laboratory's Users' Organization that "one of the first aims of experiments on the NAL accelerator system will be the detection of a neutrino. I feel that we then will be in business to do experiments on our accelerator." Later that year experiment E-21, named "Neutrino Physics at Very High Energies" and run by a Caltech group, was the first to detect neutrinos at the new laboratory.

HARVARD - PENNSYLVANIA - WISCONSIN COLLABORATION*

NAL NEUTRINO PROPOSAL

ABSTRACT

We propose here an experiment, using neutrinos in the energy range 10 - 100 GeV, that will permit us to: (1) search for an intermediate vector boson W through the reaction $\nu_\mu + Z \to \mu^- + W^+ + Z$, up to a W mass of $\simeq 10$ GeV/c^2 at 200 GeV operation of NAL; both the leptonic and hadronic decay modes will be detected; (2) measure the cross section for the diagonal 'point' four-fermion interaction $\nu_\mu + Z \to \mu^- \mu^+ \nu_\mu Z$; (3) measure $d^2\sigma/dq^2 d(E_\nu - E_\mu)$ in the region $q^2 \to$ very large, $(E_\nu - E_\mu) \to$ very large, i.e., the deeply inelastic scattering region; (4) measure $d^2\sigma/dq^2 d(E_\nu - E_\mu)$ and $\sigma_{tot}(E_\nu)$ for the reaction $\nu_\mu + p \to \mu^- +$ (anything). The device that will be used to accomplish these experiments consists of a large hydrogen target, a heavy metal, fine-grained total absorption calori-meter and a large iron core magnet.

*In alphabetical order: E. W. Beier (P), D. Cline (W), A. K. Mann (P) J. Pilcher (H), D. D. Reeder (W), C. Rubbia (H), plus at least 3 post doctoral people and several graduate students.

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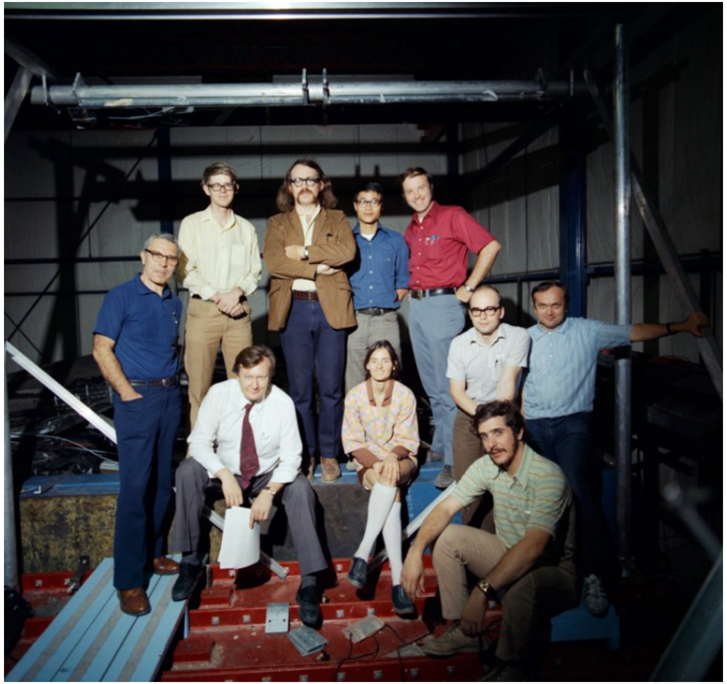


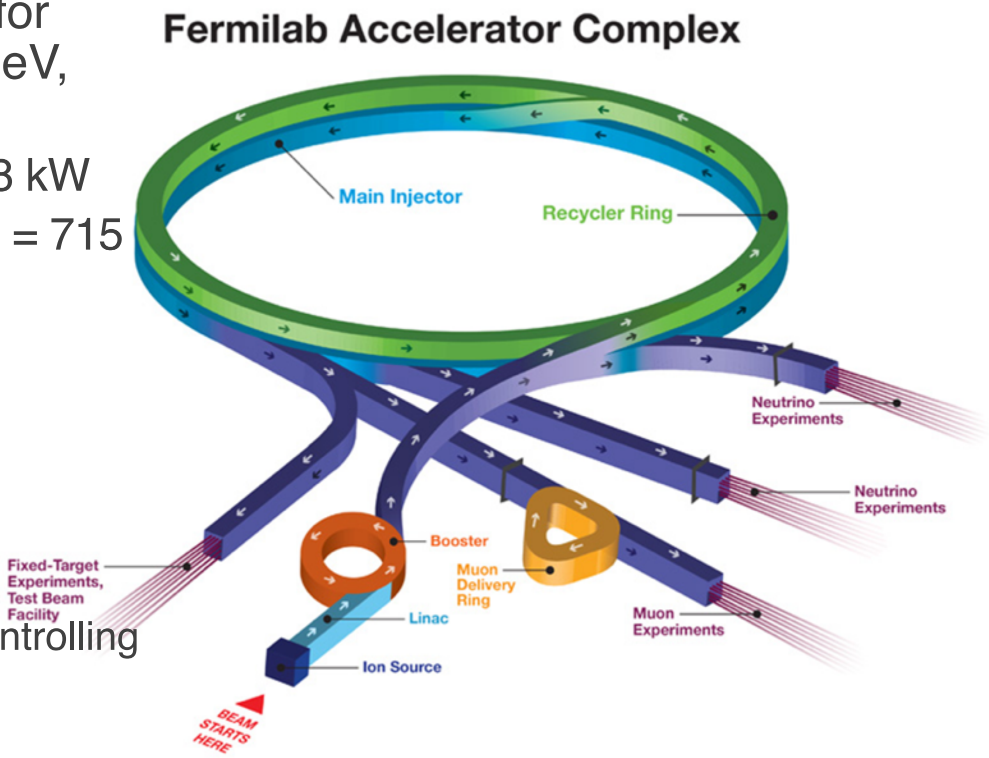
Proton Economics in 1971

- Program was 400 GeV Fixed target program
  - Resonant extraction from the Main Ring
    - 5 second fill and ramp up
    - 4 second flat top
    - 4 second ramp down
    - Shared amongst Meson, Neutrino, Proton experiments
- Booster requirements
  - Main Ring was 13.25x Booster Circumference
  - 12 injections of 2-3 e12
  - 1.08e16 per hour

The Fermilab Accelerator Complex Today

- The Fermilab complex delivers protons for neutrino production at both 8 and 120 GeV, with a present capability:
  - 8 GeV: 4.6×10^{12} protons @ 15 Hz = 88 kW
  - 120 GeV: 5.0×10^{13} protons @ 0.75 Hz = 715 kW

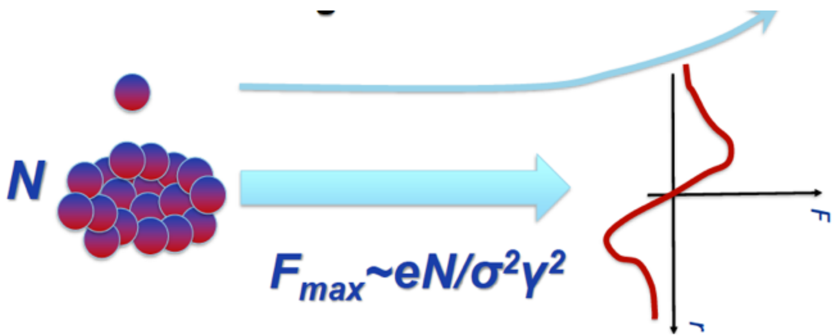
- Present limitations
  - Booster pulses per second
    - The Booster magnet/power supply system operates at 15 Hz
  - Rings Beam Loss
    - Higher Power operation is all about controlling beam loss
  - Target systems capacity
    - Limited to ~800 kW – changing summer 2020!



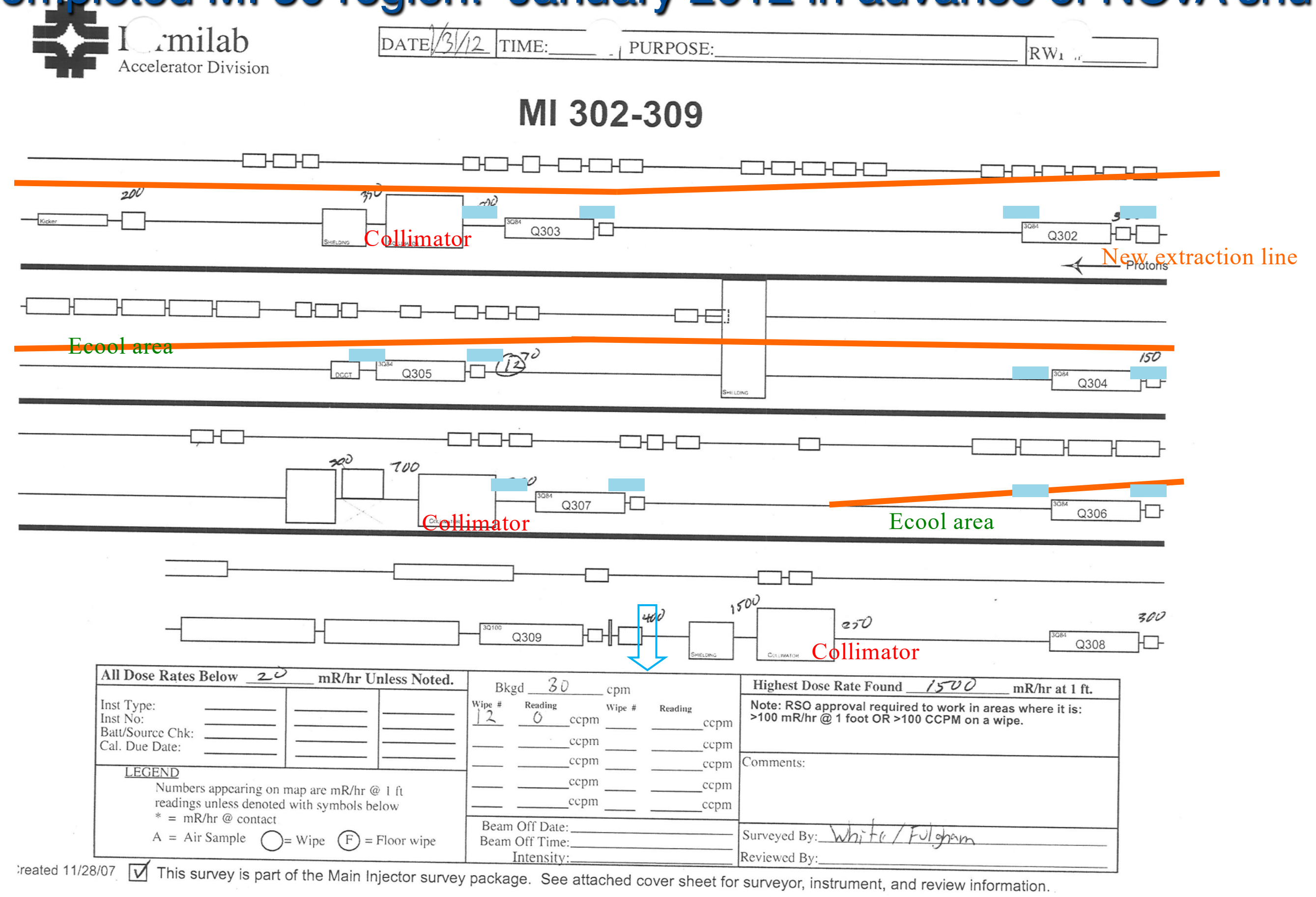
Increasing Beam Intensity

- Intensity Frontier experiments
  - All about beam loss
  - Defocusing force is nonlinear
    - Beam Intensity (N)
    - Beam Size (σ)
    - Beam Energy (γ)
  - Beam Loss:
    - Radiological controls: personnel safety, ground water
    - Radiological activation: maintenance ALARA
    - Radiological activation: component performance / degradation (cables and electronics)

    - Capture in a controlled fashion: collimators
    - Or 'lose' at lower energy
  - Protons – do not have synchroton radiation to control beam size!

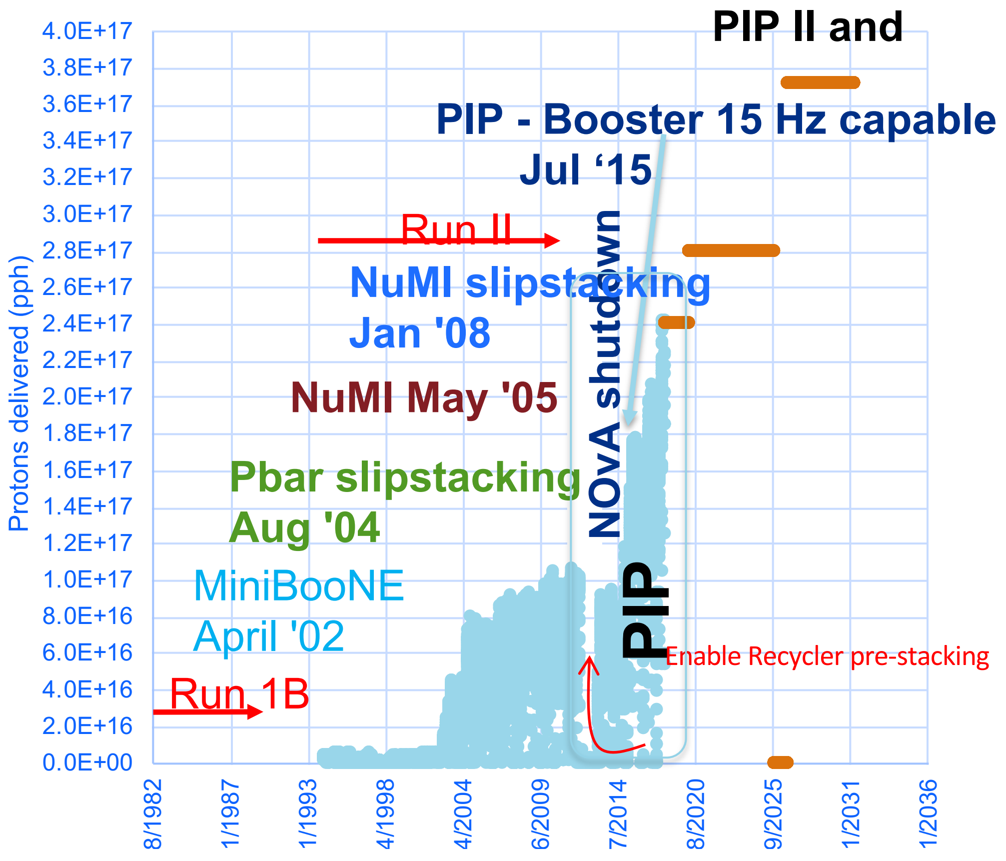


Rad Survey Completed MI 30 region: January 2012 in advance of NOvA shutdown



Progress: Beam through Booster

- Collider Era Run 1b
  - April 12 1994 – April 12 1995:
    - 2.19e19 protons
    - 6.2e16 per day (354 days)
- Tevatron Fixed Target
  - Oct 1 1996 – Oct 1 1997
    - 1.14e19 protons
    - 3.4e16 per day (332 days)
- Collider Run II
  - Oct 1 2001 – March 31 2002
    - 9.6e18 protons
    - 5.3e16 per day (181 days)
- MiniBoone + Collider:
  - Feb 1 2003 – Aug 31 2003
    - 1.29e20 protons
    - 7e17 per day (184 days)



Fermilab

Proton Plan: 2005-2007

- Reliability
  - Linac Power Amplifier 7835's
- Booster Repetition Rate limits
  - Magnet & RF cooling
  - RF Cavity performance
  - Goal: 9 Hz to support NOvA
    - Cavity was ~7-8 Hz
    - Beam was ~6-7 Hz
- Loss Control
  - Booster Alignment & Instrumentation
  - Booster Correctors
  - MI Large Aperture Quads
  - MI Collimation system

Executive Summary

Fermilab is poised to significantly improve our understanding of neutrino oscillation. The MiniBooNE experiment [1] using the Booster Neutrino Beam (BNB) will confront the puzzling ν_e oscillation results from LSND within the next year. The MINOS experiment [2] will detect neutrinos produced by the NuMI facility in early 2005 to confirm the presumed $\nu_\mu \rightarrow \nu_\tau$ oscillation results from Super-Kamiokande, and to make precision measurements of the mixing parameters. The proposed NOvA experiment will use off-axis neutrinos from the NuMI facility to detect $\nu_\mu \rightarrow \nu_e$ oscillations. The investment in accelerator upgrades described in this document will maximize the physics reach of these experiments.

We present a three-year plan for increasing the proton intensity delivered to the 120 GeV and 8 GeV neutrino beams, with upgrades to the Linac, Booster and Main Injector. Once the elements of this plan are completed, NuMI will accumulate approximately 3.4E20 protons per year. The 8 GeV beamline will receive approximately 2.2E20 protons per year. This latter estimate is highly dependent on the performance of the Booster and other efficiency factors.

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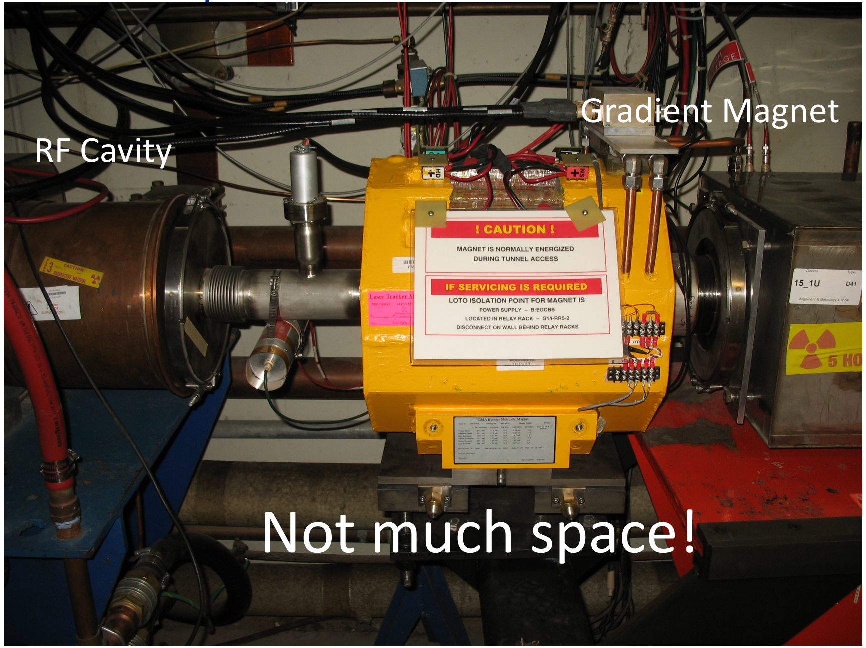
  - Booster Correctors
  - MI Large Aperture Quads
  - MI Collimation system

Prior to 2007, Booster had static corrector system
minimal orbit, tune, chromaticity correction

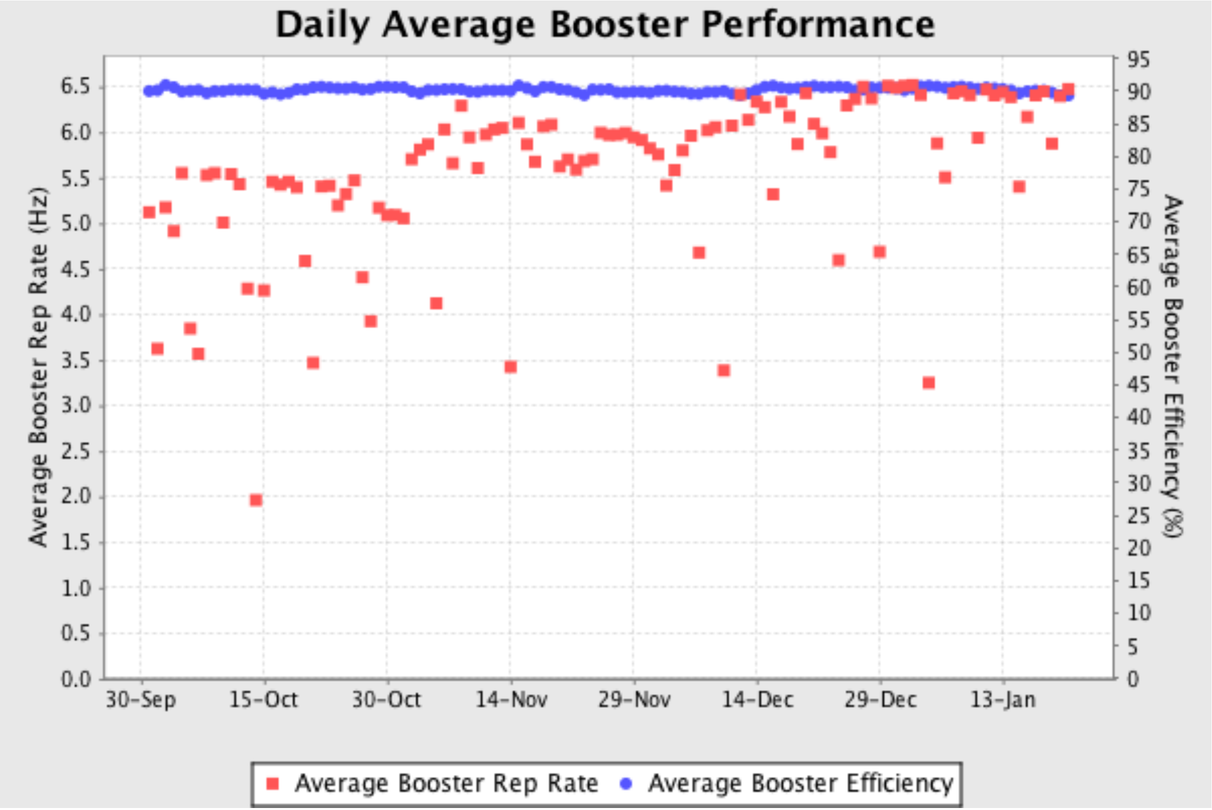
Ramped Booster corrector: One package
Dipole, Quadrupole, Skew Quad, Sextupole, Octupole



Booster Operations

- 2011
  - Tevatron Collider
    - Pbar production
  - Booster Neutrino Beam
    - 8 GeV
  - NuMI
    - 120 GeV

  - 6 – 6.5 Hz
  - 90% efficiency (injected/extracted)



Fermilab

Booster Operations

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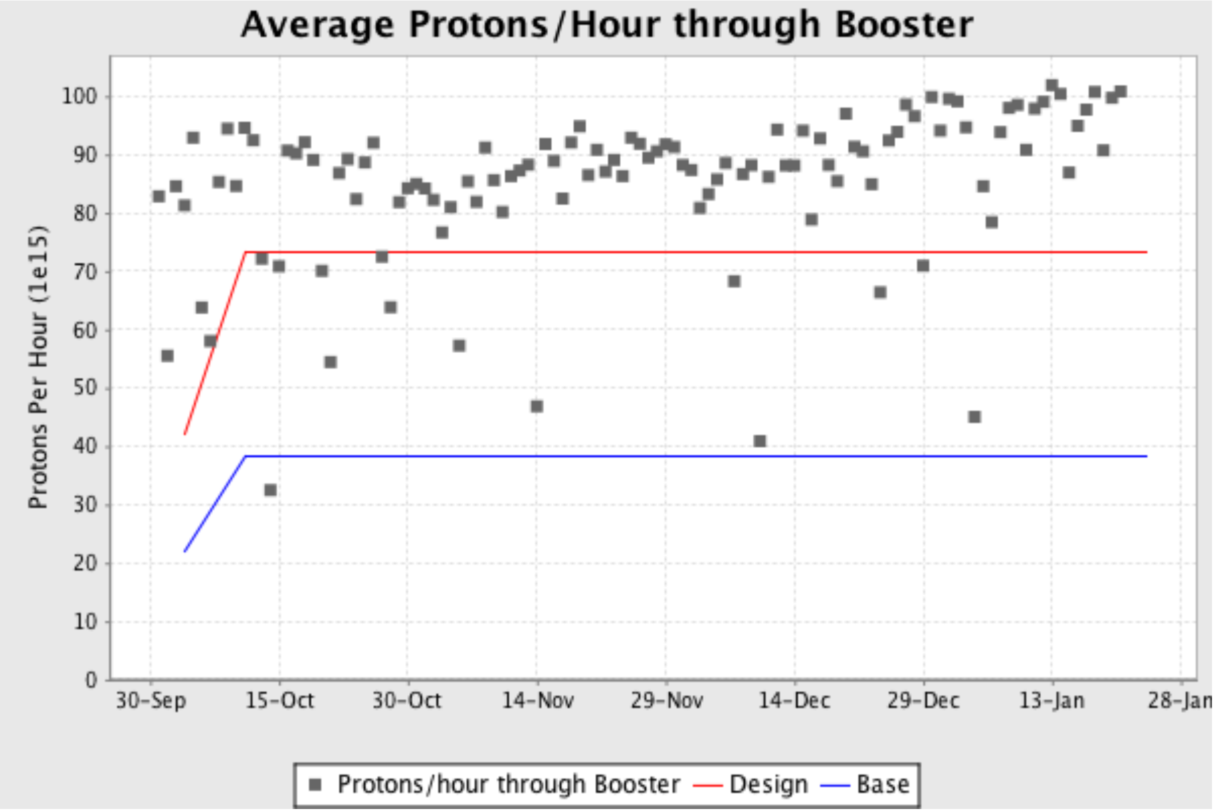
    - 120 GeV

  - 6 – 6.5 Hz
  - 90% efficiency (injected/extracted)

  - 1e17 per hour peak



Fermilab

Strategy for the past ~10 years
Proton Improvement Plan (PIP)

The near-term goal is to double the Booster beam repetition rate to 15 Hz, while addressing reliability concerns

  - Required for simultaneous operations of NOvA, g-2, Mu2e, SBN
  - 700 kW to NOvA: 4.9e13 @ 120 GeV @ 0.75 Hz
- Design Criteria
  - 15 Hz beam operations at 4.2×10^{12} protons per pulse (80 kW)
  - Linac/Booster availability > 85%
  - Residual activation at acceptable levels
  - Useful operating life for the Linac through 2023 and the Booster through 2030
- Scope
  - 15 Hz Capability:
    - RF upgrades, cavity refurbishment
    - Power and water distribution
  - Reliability: >85% uptime, reduce operational risk
    - Drift Tube Linac RF replacement ⇒200 MHz klystrons/modulators
    - Additional Booster RF cavities
    - Power and water distribution
  - Beam Quality and Losses: RFQ, dampers, collimators/absorbers
    - To maintain activation at current levels or lower
    - Linac laser notcher
- Execute over the years 2011 – 2019

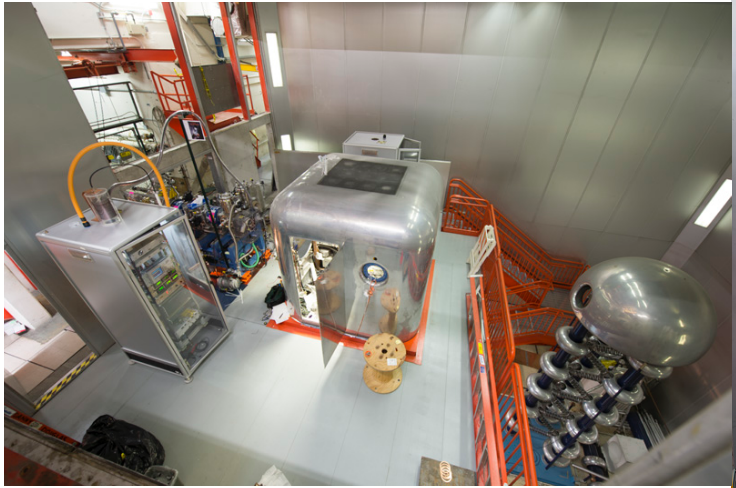
Most obvious for proton power

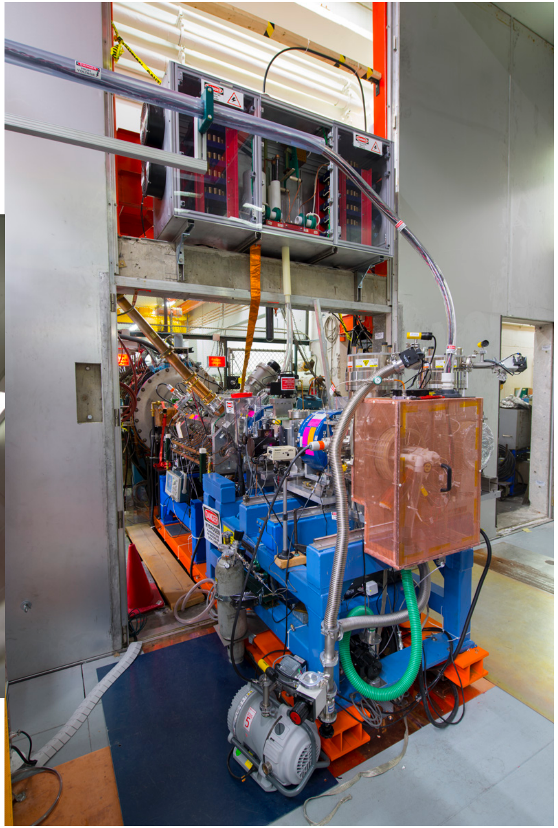
Key for POT and uptime

Fermilab

PIP RFQ Injector

- Started in 2009 (on Proton Plan)
  - RFQ Delivered 2011
  - Solenoids 2012
  - Quads/Trims 2012
  - Buncher 2012
  - Install Fall 2012
  - 1st Beam Nov 2012
  - Fully Commissioned Jan 2013
- Completed in 2013



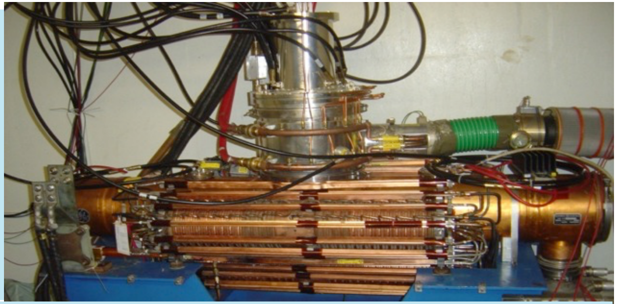


PIP – Booster Cavity Refurbishment

Cavity work: 2 – 4 weeks
Tuner work: 4 weeks
Tuner installation: 1+ week
RF testing: 1+ week

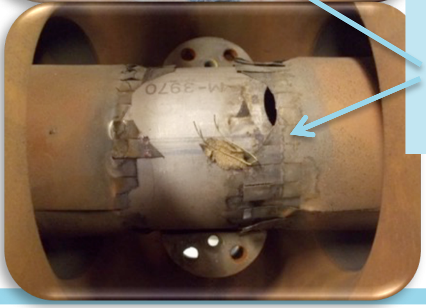
Potential delays: vacuum and water complications

Rate of repair improved by 1.5 wk



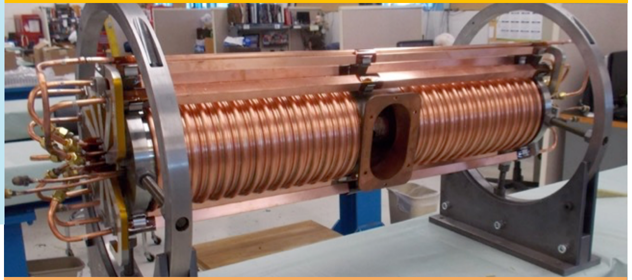
Additional 20th cavity being tested 15 Hz (salvaged original cavity – major rebuild)

suitable ferrite for new tuners



Old cavities had many problems - especially the tuners:

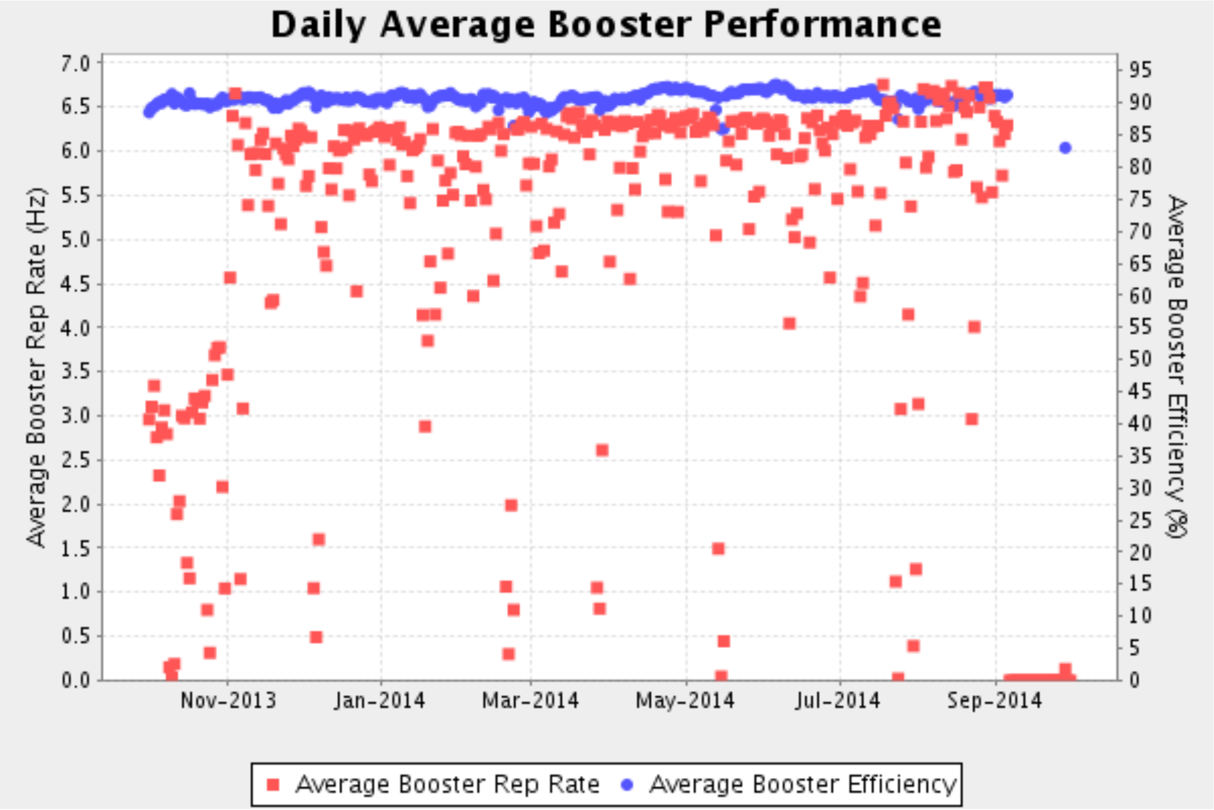
- Water Leaks
- Burnt RF Fingers
- Connection Flange



First new tuner – built & tested

Booster Operations

- 2014
  - Booster Neutrino Beam
    - 8 GeV
  - NuMI
    - 120 GeV
  - 6 – 6.5 Hz
  - 92% efficiency (injected/extracted)
  - RF Cavities refurbished one at a time
    - Available voltage restricted flux



Fermilab

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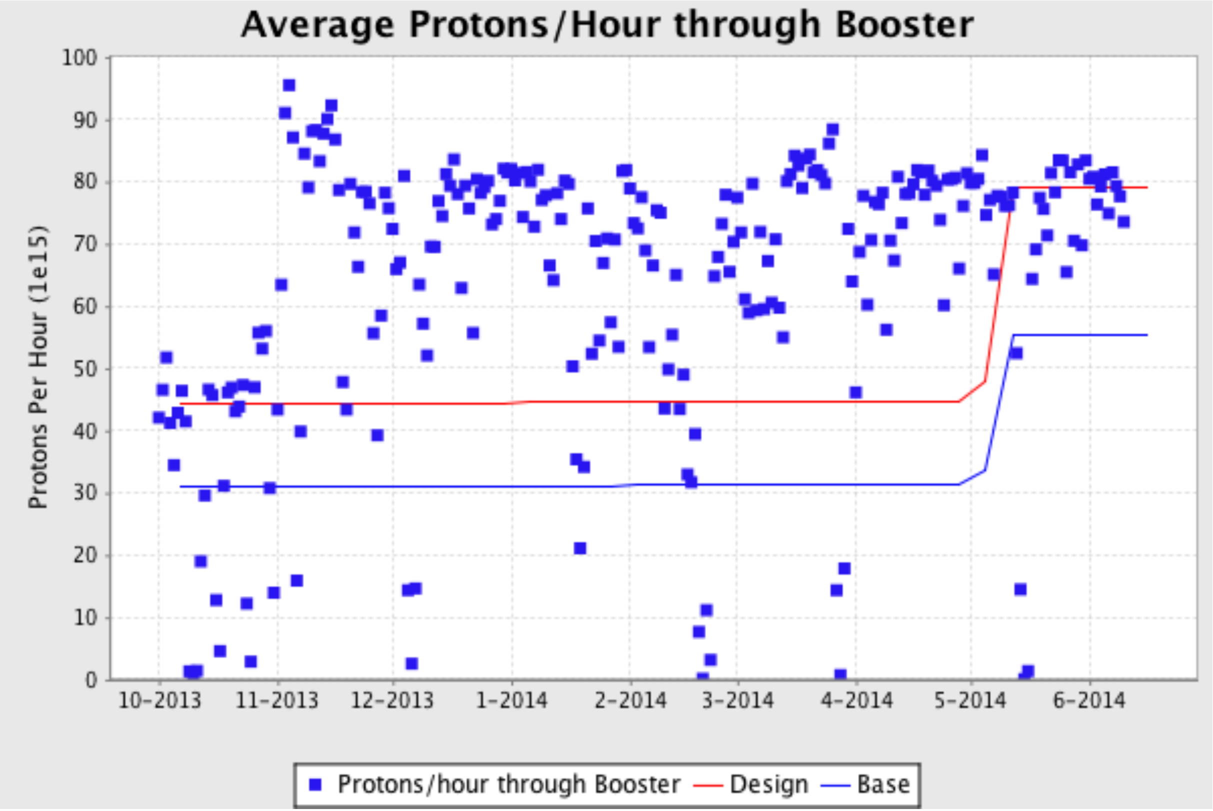
  - 8e16 per hour

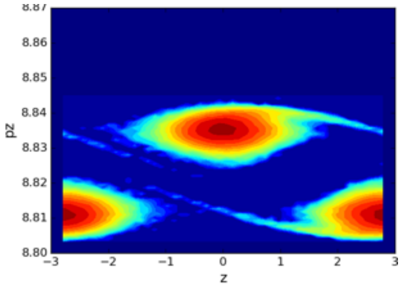


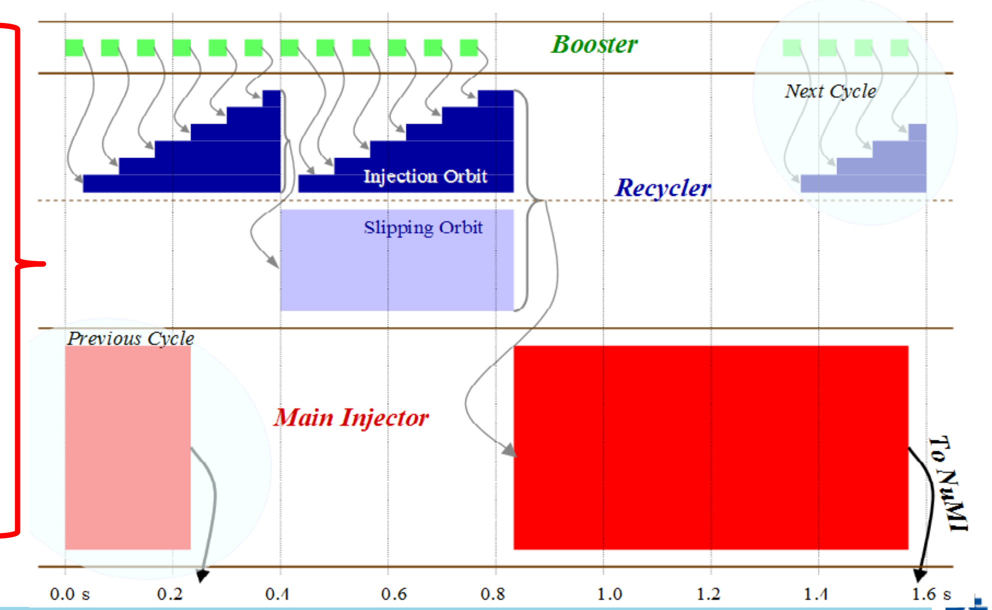
Fermilab

Slip Stacking for Intensity Increases

- The 15 Hz Booster injects 12 “batches” into the Recycler
- These are then transferred to the Main Injector, which accelerates and extracts them them as the loading process repeats in the Recycler
- Inherently a ’lossy’ process
- Clean kicker gaps important to minimize uncontrolled losses

“slip-stacking” cleverly gets around limits on Booster batch size by allowing two batches to “slip” together, doubling the number of protons in each MI cycle



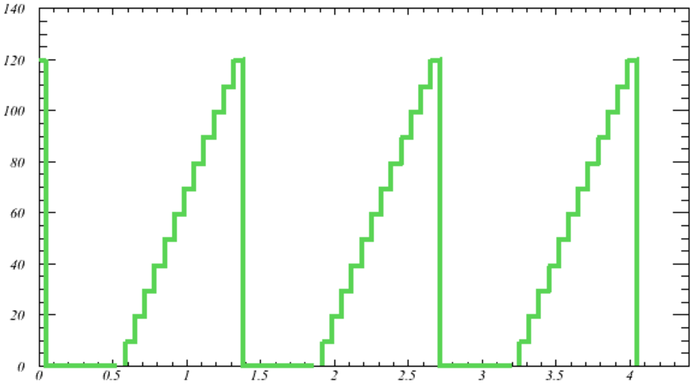


Increasing beam power: NOvA Upgrades

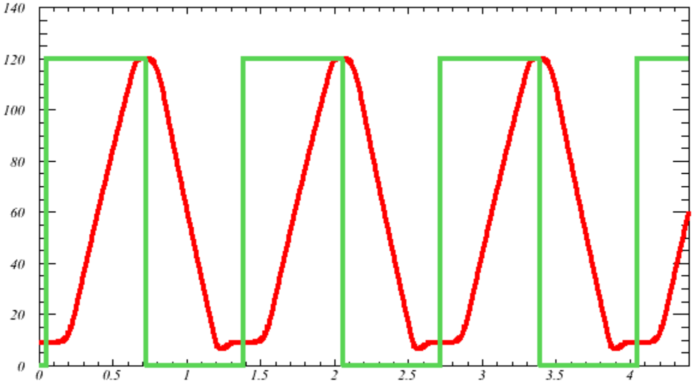
- Move slip-stacking to recycler
- 11 batch -> 12 batch
- Increase Main Injector ramp rate (204 GeV/s -> 240 GeV/s)
- ~Double POT with only ~10% increase in per-pulse intensity

- Dependent on 15 Hz capability of Booster RF Cavities

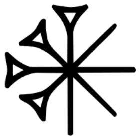
- Clean kicker gaps important to minimize uncontrolled losses



Recycler



Main Injector

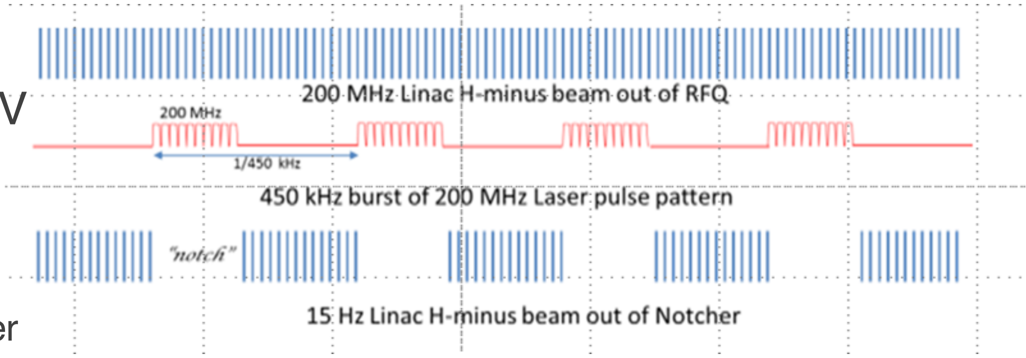


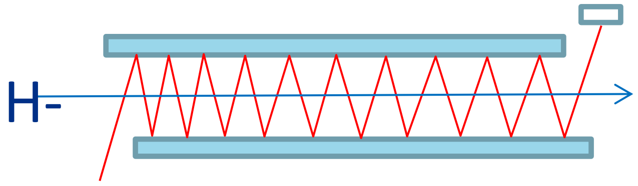
Sumerian cuneiform for ANU

Thanks to Phil Adamson for the animation

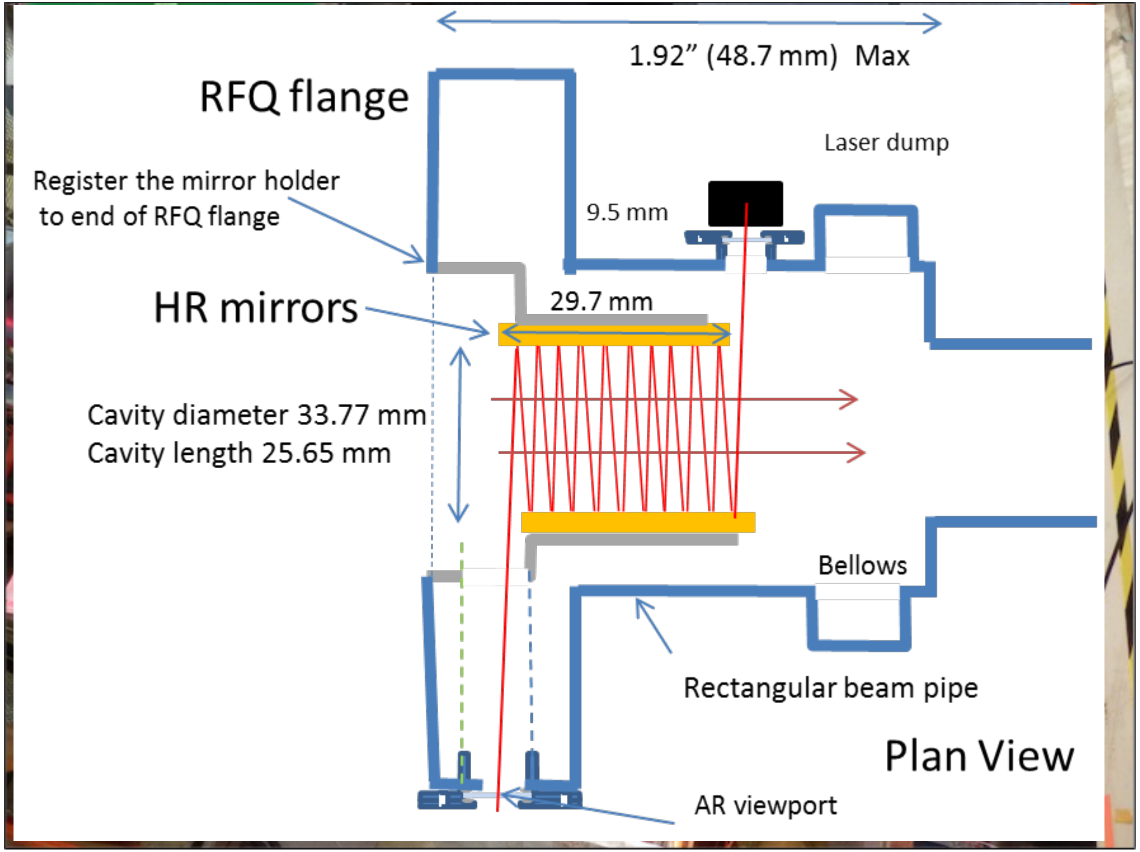
Linac Laser Notcher

- Booster beam needs a kicker gap
  - pre 2018: create a gap at ~500 MeV by kicking out 3 (of 84) buckets
    - Beam loss in the Booster,
      - absorbed by components
      - eventually by dedicated absorber
- Can we notch at lower energy?
  - ~80 nsec of notch required
  - In the linac?
  - Laser stripping at the output of the RFQ : 750 keV

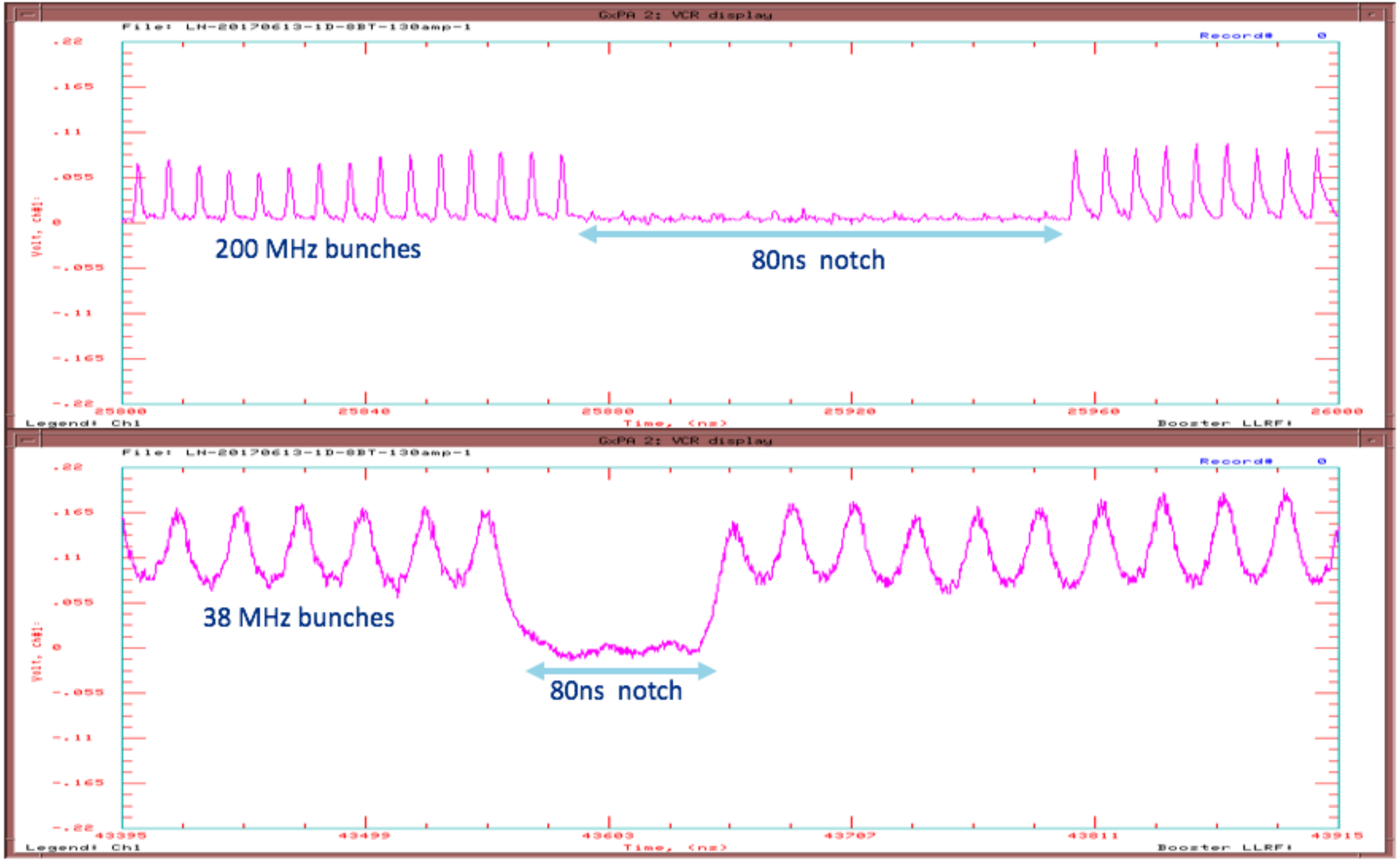




New 750 keV RFQ Injection Line (RIL)

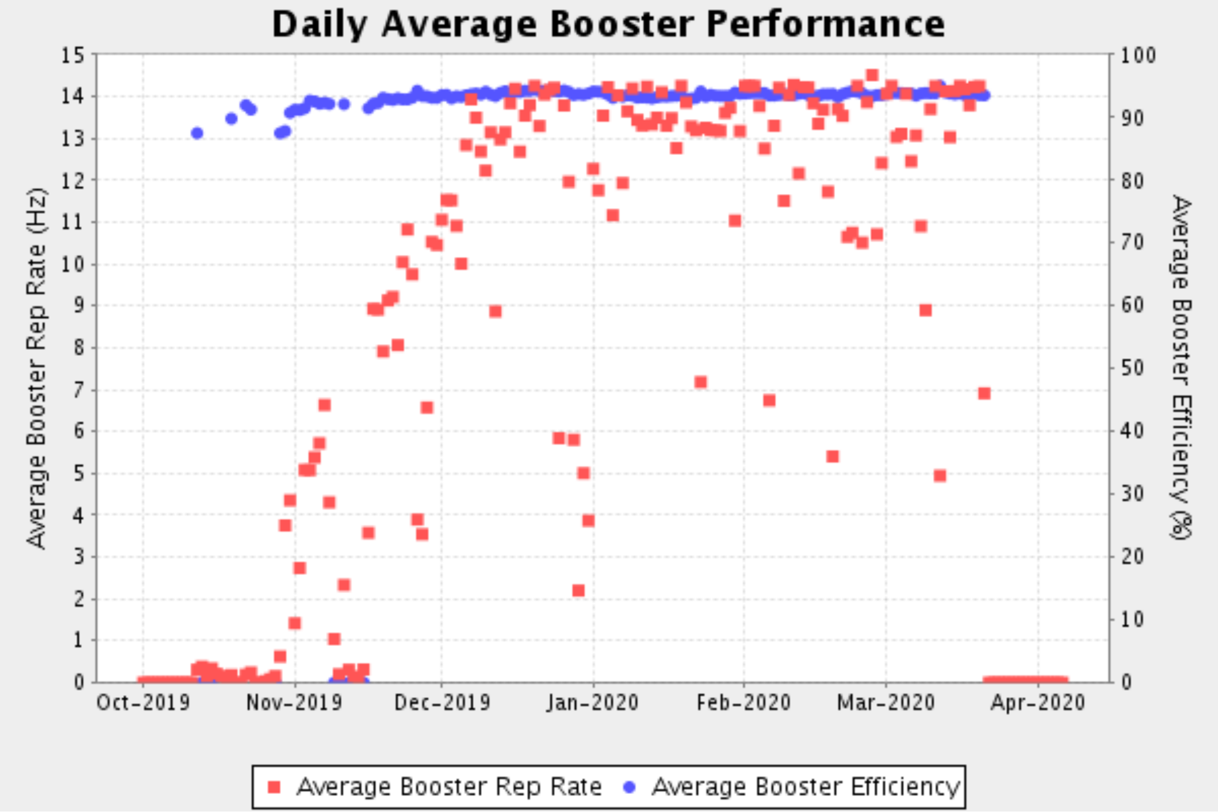


Notch survives in the Booster



Booster Operations

- 2020
  - Booster Neutrino Beam
    - 8 GeV
  - NuMI : NOvA
    - 120 GeV
  - Muon program : g-2
    - 8 GeV
  - 14+ Hz
  - 94% efficiency (injected/extracted)
  - 2x beam throughput
  - Same total power loss



Fermilab

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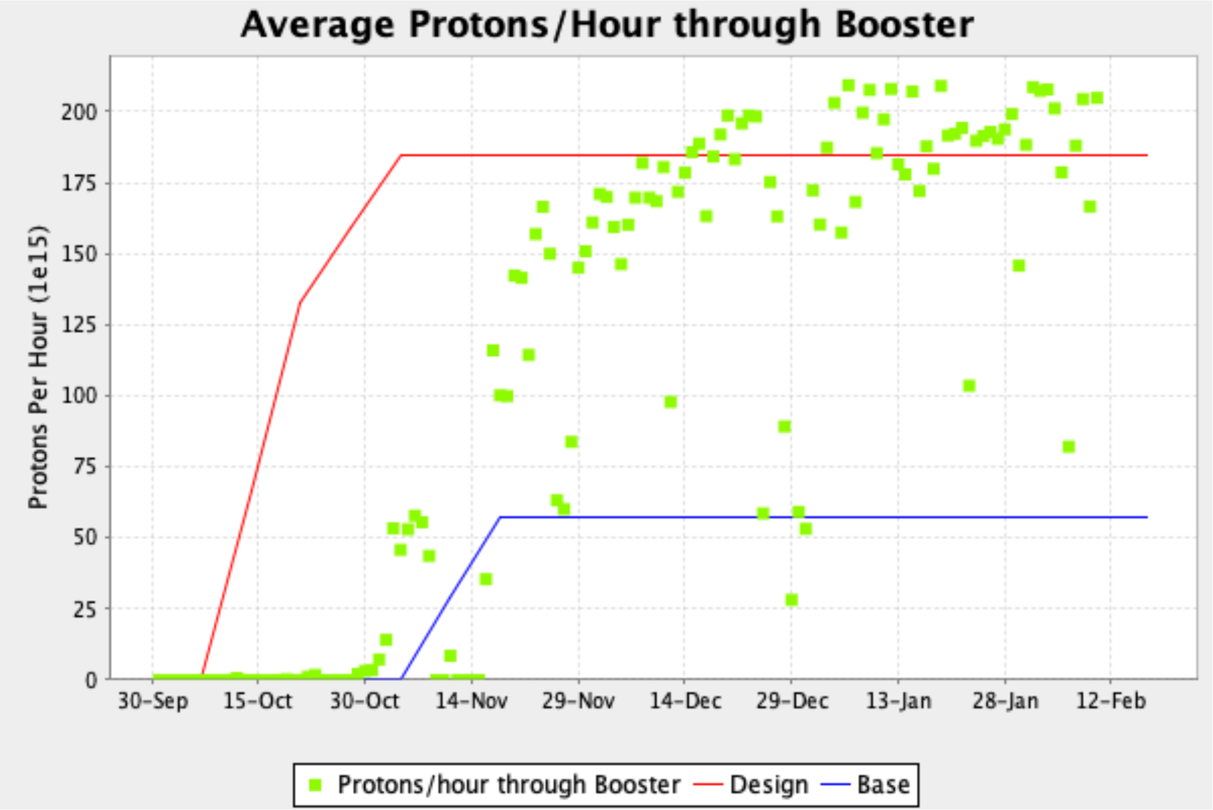
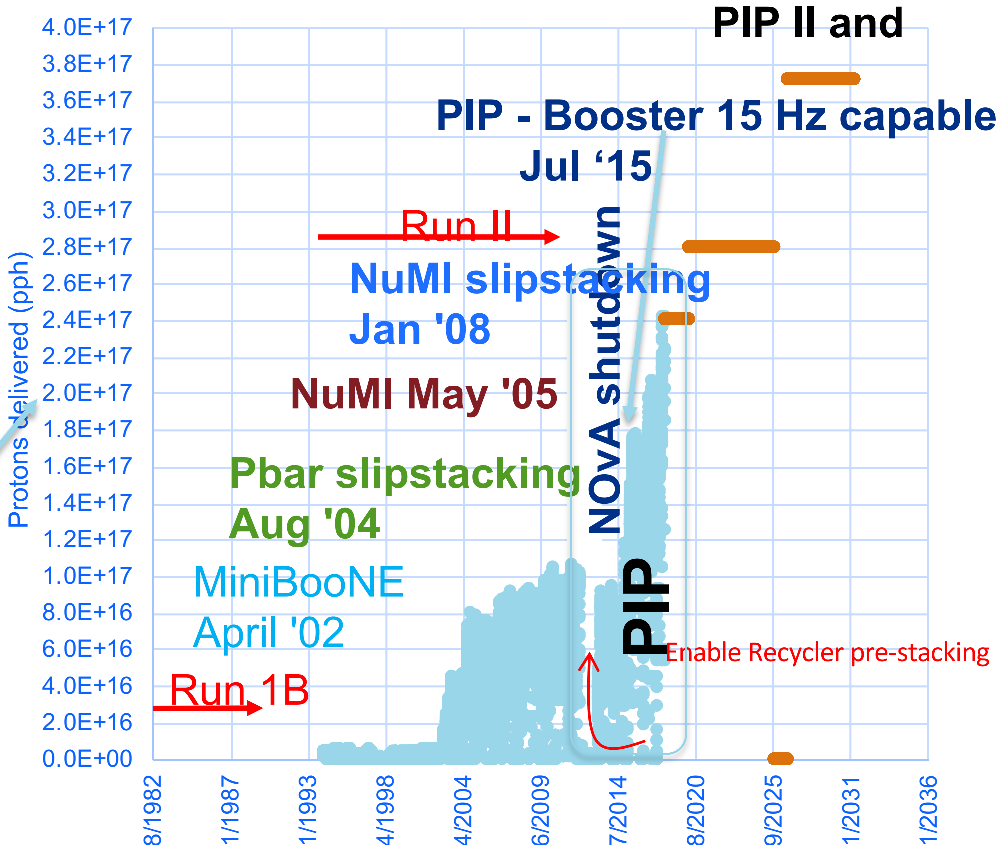


Fermilab

Progress: Beam through Booster

- Recent milestones and records:
  - Full 15 Hz Booster operation
  - 766 kW for one hour to NuMI (PIP goal: run reliably at 700 kW)

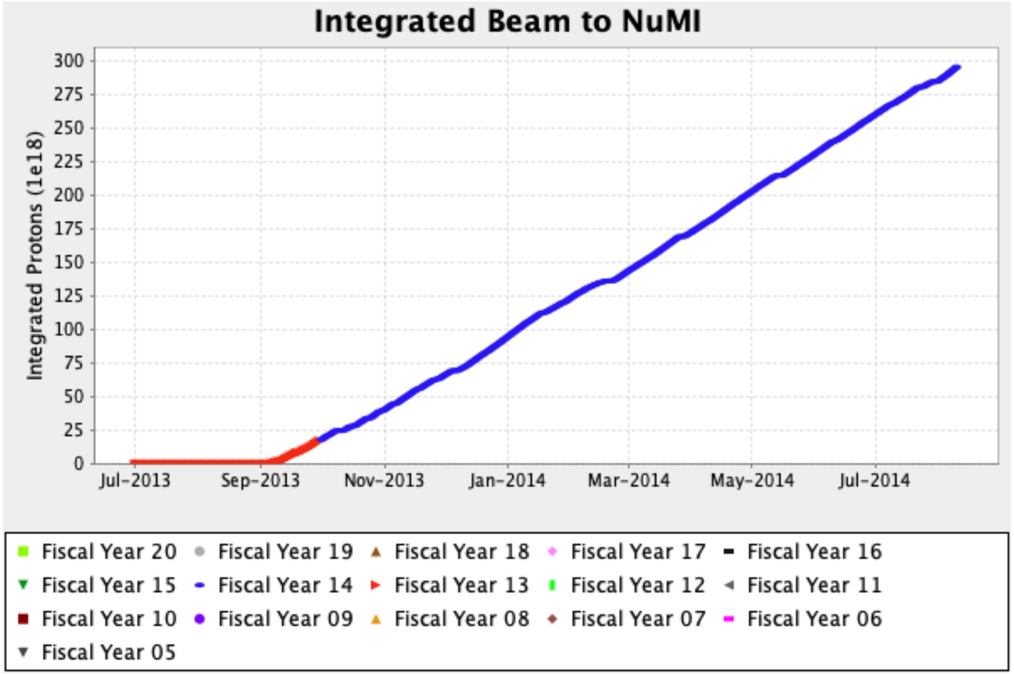


Booster delivers E1a exposure request in less than an hour

The NOvA Program

1. **Can we observe the oscillation of muon neutrinos to electron neutrinos?**
   – [First measurement of electron neutrino appearance in NOvA]
   – FERMILAB-PUB-15-262-ND
2. **What is the ordering of the neutrino masses?**
3. **What is the symmetry between matter and antimatter?**

- Beam Delivery Goal
  – 3600×10^{18} POT
    - E1A request: 0.2×10^{18}
  – 120 GeV



DUNE TDR – February 2020 FERMILAB-DESIGN-2020-01

- 1 year = 1.1e21 POT
  - 1.2 MW, 56% uptime
  - If 800 kW: 1.5x longer
  - If 2.4 MW: 0.5x shorter

~~CP~~ Sensitivity	Years (0.8-1.2-2.4 MW)
3σ, 75% δ_{CP}	20 – 13.3 – 6.7
5σ, 50% δ_{CP}	21 – 10.5 – 5.3
5σ, $\delta_{CP}={}^{\pi}/_{2}$	14 – 7 – 3.5

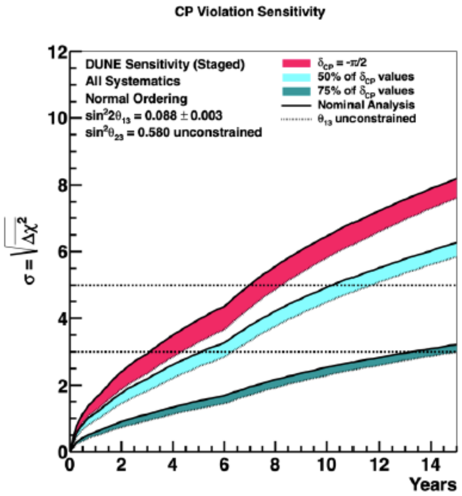


Figure 2.6: Significance of the DUNE determination of CP-violation (i.e.: $\delta_{CP} \neq 0$ or π) for the case when $\delta_{CP} = -\pi/2$, and for 50% and 75% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

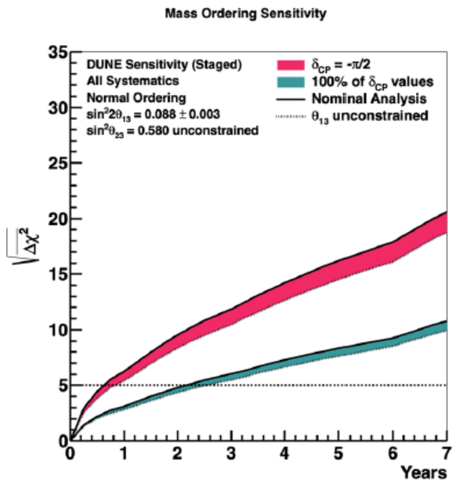


Figure 2.7: Significance of the DUNE determination of the neutrino mass ordering for the case when $\delta_{CP} = -\pi/2$, and for 100% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

Current Strategy
Proton Improvement Plan-II (P

The longer-term goal is to incre ... the Main Injector by an additional 50% and to provide i ... program, while providing a platform for the future

- Strategy
  - Increase the Booster per pulse intensity by 50%
    -
    -
  - Mo
- Design
  - De ... art of LBNF ope
  - Su ... neutrino exp
  - Pr
  - Pr
  - Pr ... ations
  - At
- Execute

Mission Need Statement
for

Proton Improvement Plan-II (PIP-II)
Project

The current beam power of 700 kW is insufficient to meet the P5 goal of delivering 120 MW-kton-years by 2035. Increasing the beam power to 1.2 MW would roughly double the DUNE data-taking rate, significantly increasing the competitive edge of the experiment by halving the time it would take to achieve significant scientific results. This in turn raises the probability that the U.S. neutrino physics program will continue to outperform the Japanese program – the closest competitor – in the 2020s.

This need for higher proton beam power comes at a time when many components of the existing Fermilab accelerator complex that delivers beam to the Main Injector – especially the linear accelerator (linac) and the Booster – are approaching 50 years old. Thus, a proton beam power upgrade is proposed to meet two main capability gap and mission need goals:

1. To reduce the time for LBNF/DUNE to achieve world-first results.
2. To sustain high reliability operation of the Fermilab accelerator complex.

Next step to higher intensity
Proton Improvement Plan-II (PIP-II)

The longer-term goal is to increase the beam power delivered from the Main Injector by an additional 50% and to provide increased beam power to the 8 GeV program, while providing a platform for the future

- Strategy
  - Increase the Booster per pulse intensity by 50%
    - Increase in injection energy to ~800 MeV
    - Increase injection frequency to 20 Hz
  - Modest modifications to Booster/Recycler/MI
- Design Criteria
  - Deliver 1.2 MW of beam power at 120 GeV, approaching 1 MW down to 60 GeV, at the start of LBNF operations
  - Support the current 8 GeV program, including Mu2e, g-2, and the suite of short-baseline neutrino experiments
  - Provide an upgrade path for Mu2e
  - Provide a platform for extension of beam power to LBNF to >2 MW
  - Provide a platform for extension of capability to high duty factor/higher beam power operations
  - At an affordable cost to DOE
- Execute over 2016 – 2027

DUNE TDR – February 2020 FERMILAB-DESIGN-2020-01

- 1 year = 1.1e21 POT
  - 1.2 MW, 56% uptime
  - If 800 kW: 1.5x longer
  - If 2.4 MW: 0.5x shorter

~~CP~~ Sensitivity	Years (0.8-1.2-2.4 MW)
3σ, 75% δ_{CP}	20 – 13.3 – 6.7
5σ, 50% δ_{CP}	21 – 10.5 – 5.3
5σ, $\delta_{CP}={}^{\pi}/_{2}$	14 – 7 – 3.5

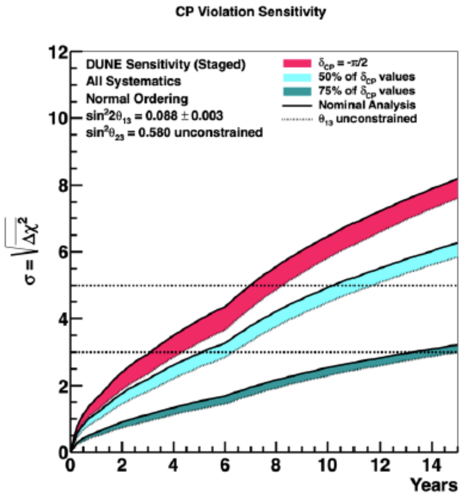


Figure 2.6: Significance of the DUNE determination of CP-violation (i.e.: $\delta_{CP} \neq 0$ or π) for the case when $\delta_{CP} = -\pi/2$, and for 50% and 75% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

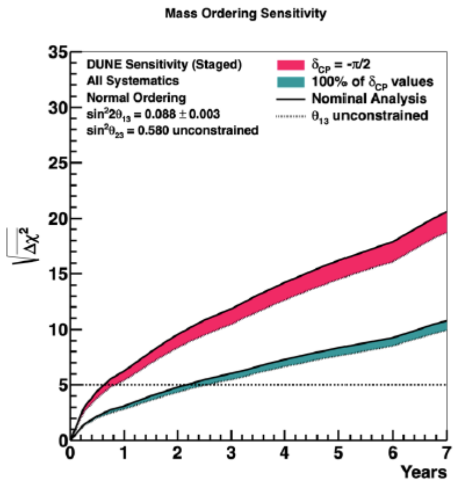


Figure 2.7: Significance of the DUNE determination of the neutrino mass ordering for the case when $\delta_{CP} = -\pi/2$, and for 100% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

PIP-II Technical Approach

- Construct a modern 800-MeV superconducting linac, of CW capable components, operating initially in pulsed mode
  - Ameliorate space-charge forces at Booster injection, allowing an increase Booster/Recycler/Main Injector per pulse intensity of ~50%, while preserving transverse & longitudinal emittance at current levels
- Accompanied by modifications to Booster/Recycler/Main Injector to accommodate higher intensities and higher Booster injection energy
- Increase Booster repetition rate to 20 Hz
  - Maintain 1 MW down to 60 GeV <u>or</u>,
  - Provide factor of 2.5 increase in power to 8 GeV program
- Described in the Preliminary Design Report
  - https://pip2-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=2261&filename=PIP-II%20Preliminary%20Design%20Report%20Version%201-17-2020.pdf&version=33

Beyond PIP: Space Charge Limit

- Losses in the Booster may be limited by the space charge tune-shift, which can drive harmonic instabilities.

total protons

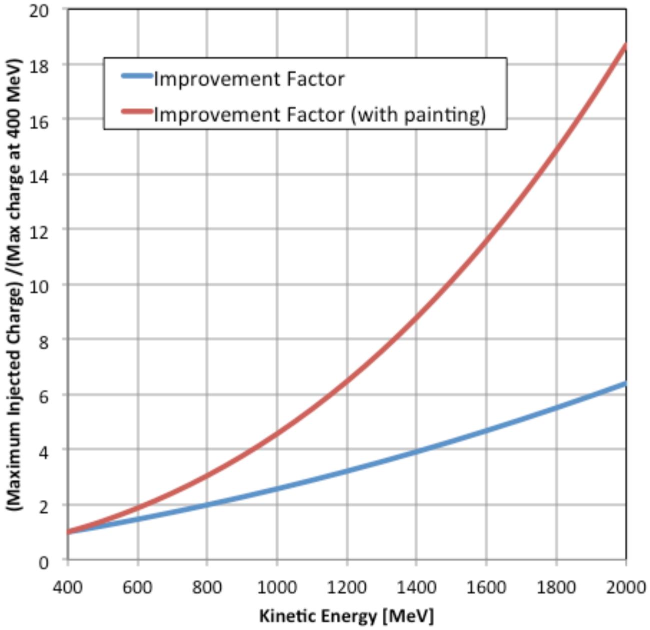
"Bunch factor" = I_{peak}/I_{ave}
(Reduce with higher RF harmonics)

$$\Delta\nu \approx \frac{N r_0}{2\pi\epsilon_N \beta\gamma^2} F B \lesssim .2$$

= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

normalized emittance

$\epsilon_N = \epsilon\beta\gamma = \text{constant}$



- So the maximum injected charge grows rapidly with increasing energy

$$\begin{aligned} N_{max} &\propto \beta\gamma^2 && \text{without painting} \\ &\propto \beta^2\gamma^3 && \text{painted to fill physical aperture} \end{aligned}$$

doesn't include improvement of going to uniform distribution with painting

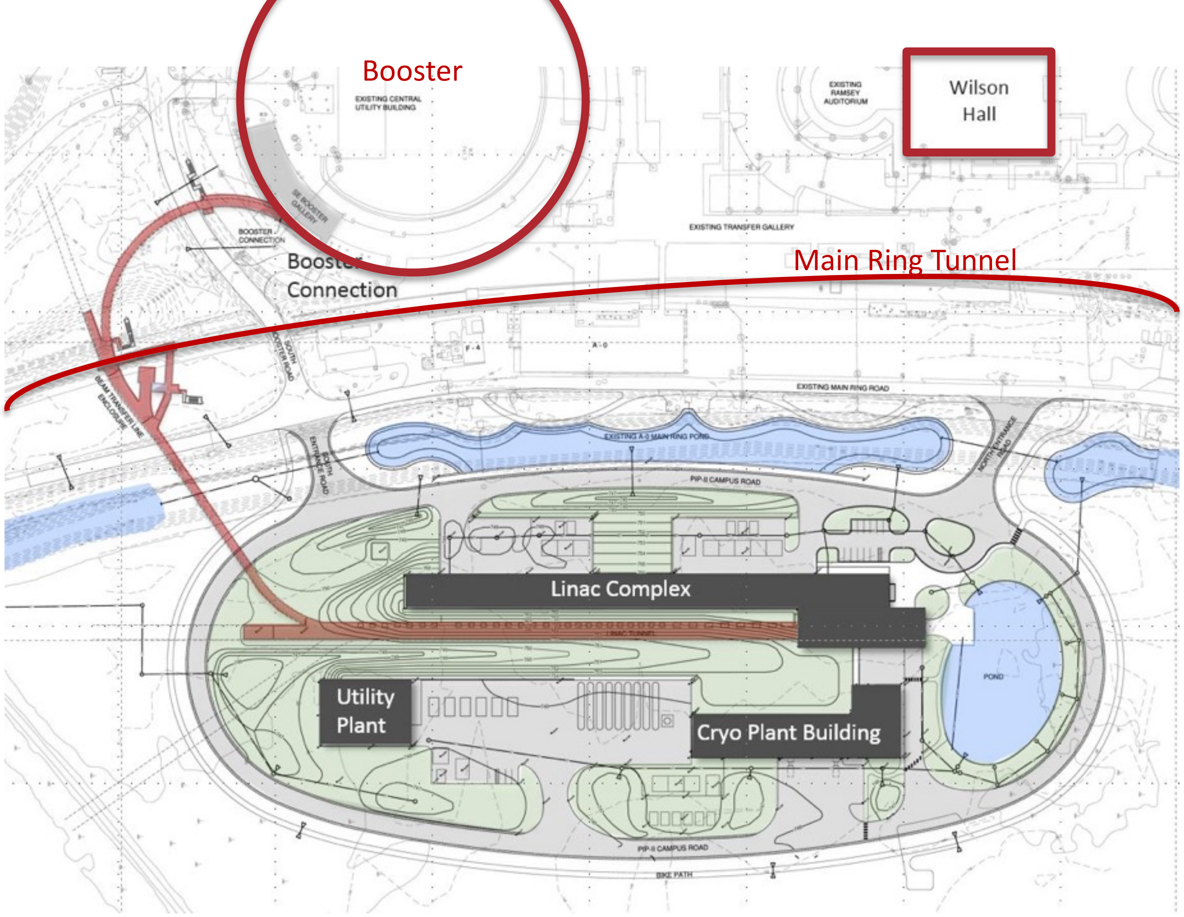
Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.54	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	17	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Upgrade Potential (800 MeV)	NA	>100*	kW
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	166	kW
Beam Power to 8 GeV Program (max)	32	83	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33**	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	0.7**	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

**NOvA operations at 120 GeV

PIP-II Components

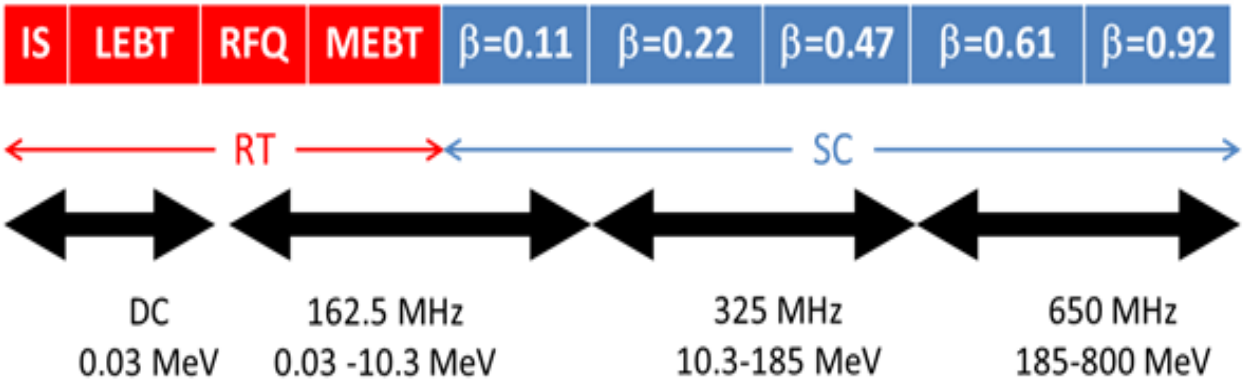
- 800 MeV linac
  - Warm Front End
  - SRF section
- Linac-to-Booster transfer line
  - 3-way beam split to: (1) Beam dump, (2) Booster & (3) Mu2e-II
- Upgraded Booster
  - 20 Hz, 800 MeV injection
    - New injection area
    - Resonant Magnet Upgrade
- Upgraded Recycler & MI
  - RF in both rings
- Conventional Facilities
  - Includes 2 empty slots at the linac end (L≈23 m)
  - Up to 1 GeV
- Cryogenic Plant



Fermilab

SC Linac - Main Part of PIP-II

- SC Linac consists of
  - Room temperature front end (up to 2.1 MeV)
  - SC (cold) linac
    - 5 types of SC cavities: HWR, SSR1, SSR2, LB650, HB650
- 3 RF frequencies are used for acceleration



β in the above figure: optimal for HWR, SSR1, SSR2; geometric for LB650, HB650

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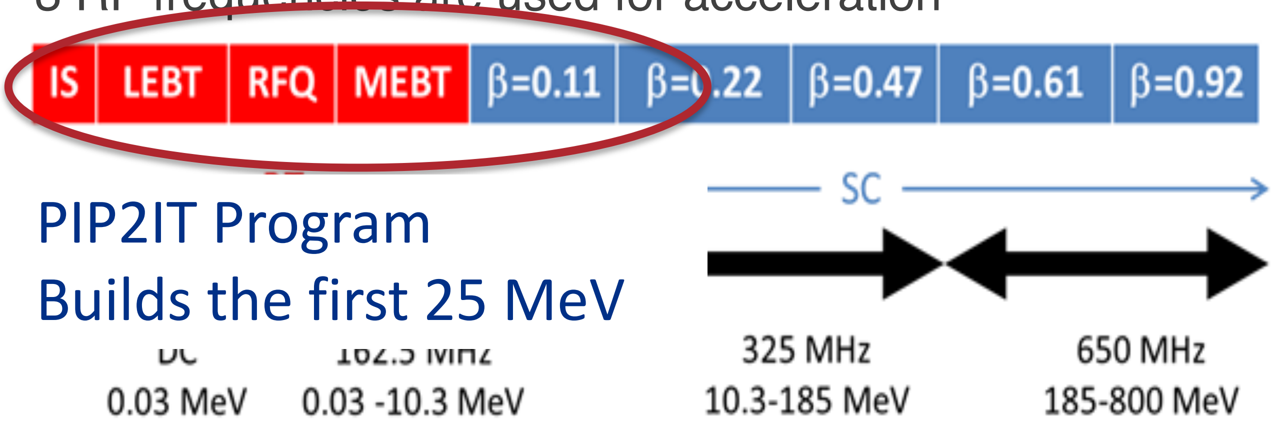

PIP2IT Program
Builds the first 25 MeV

β in the above figure: optimal for HWR, SSR1, SSR2; geometric for LB650, HB650

PIP2IT: CMTF building at north end of campus

- Key development
  - Flexible beam pattern
  - Bunch by bunch chopping system
    - 162.5 MHz
    - 500 V switch at 1 nsec
  - 2 mA CW capability
  - 2 Cryomodules arrived 2019
    - HWR at 2K in February
  - H^- beam April(?) - October

DUNE TDR – February 2020 FERMILAB-DESIGN-2020-01

- 1 year = 1.1e21 POT
  - 1.2 MW, 56% uptime
  - If 800 kW: 1.5x longer
  - $\boxed{\text{If 2.4 MW:}}$ 0.5x shorter

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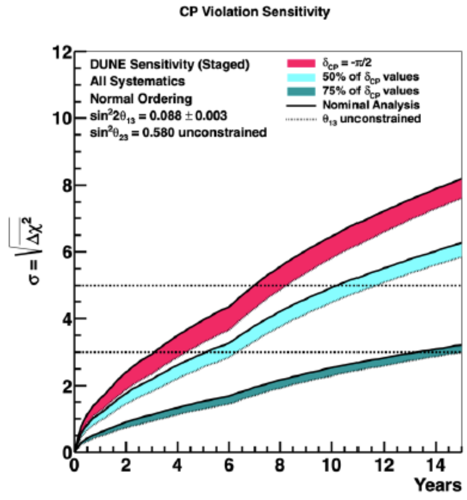


Figure 2.6: Significance of the DUNE determination of CP-violation (i.e.: $\delta_{CP} \neq 0$ or π) for the case when $\delta_{CP} = -\pi/2$, and for 50% and 75% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

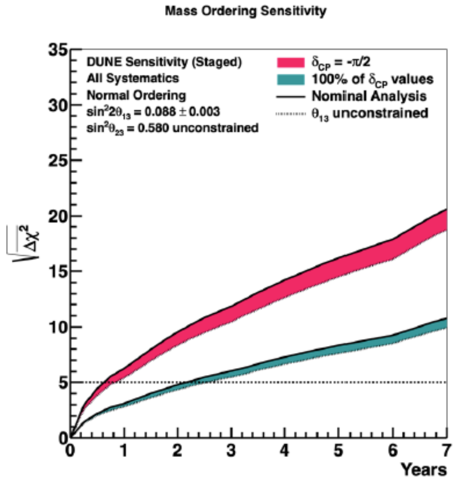


Figure 2.7: Significance of the DUNE determination of the neutrino mass ordering for the case when $\delta_{CP} = -\pi/2$, and for 100% of possible true δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed. The width of the band shows the impact of applying an external constraint on $\sin^2 2\theta_{13}$.

Booster Upgrades (~203x)

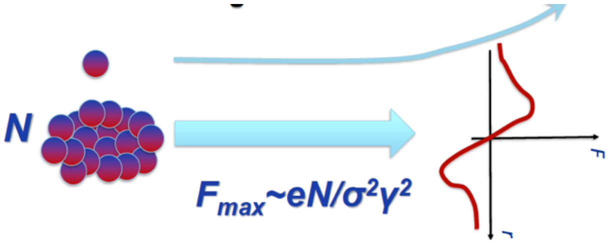
- 2.4 MW requires 1.5×10^{14} particles from MI every 1.2 s @ 120 GeV
  - Every 0.6 sec @ 60 GeV
- Current model (Slip-stacking in Recycler) is not an option at these intensities
  - Need to box-car stack $6 \times 2.5\times10^{13}$ protons in less than 0.6 sec
  - >10 Hz rep-rate
  - Or inject a long (linac) pulse directly into Main Injector
- Booster is not capable of accelerating 2.5×10^{13} no matter what the injection energy
- 4x intensity (without slip stacking!) so space charge even more important
- ***Achieving 2+ MW will require replacement of the Booster with either a multi-GeV pulsed linac or a rapid cycling synchroton (RCS) fed by a ≥ 0.8 GeV linac***
  - Deliver 2.4 MW @ 60-120 GeV from the Main Injector to the LBNF beamline in support of the DUNE experiment
  - Deliver up to 80 kW @ 8 GeV to support g-2, Mu2e, and short-baseline neutrinos
  - Deliver ~100 kW @ 800 MeV to support a second generation Mu2e

Novel Ways to Mitigate Space Charge

*Danilov, Nagaitsev, PRSTAB 2010

- Non-linear integrable optics
  - All synchrotrons ever built are based on linear optics (magnetic quadrupoles). Non-linearities are handled perturbatively, and eventually lead to instabilities.
  - Is has been shown* that non-linear magnetic fields that satisfy a very particular set of conditions can result in stable orbits, but without a unique tune
    - Extremely insensitive to harmonic instabilities
    - Stable up to space charge tune shifts of order unity!

- Studying these approaches at FAST / IOTA (NML)
  - Electron beams
  - Specially designed non-linear magnets



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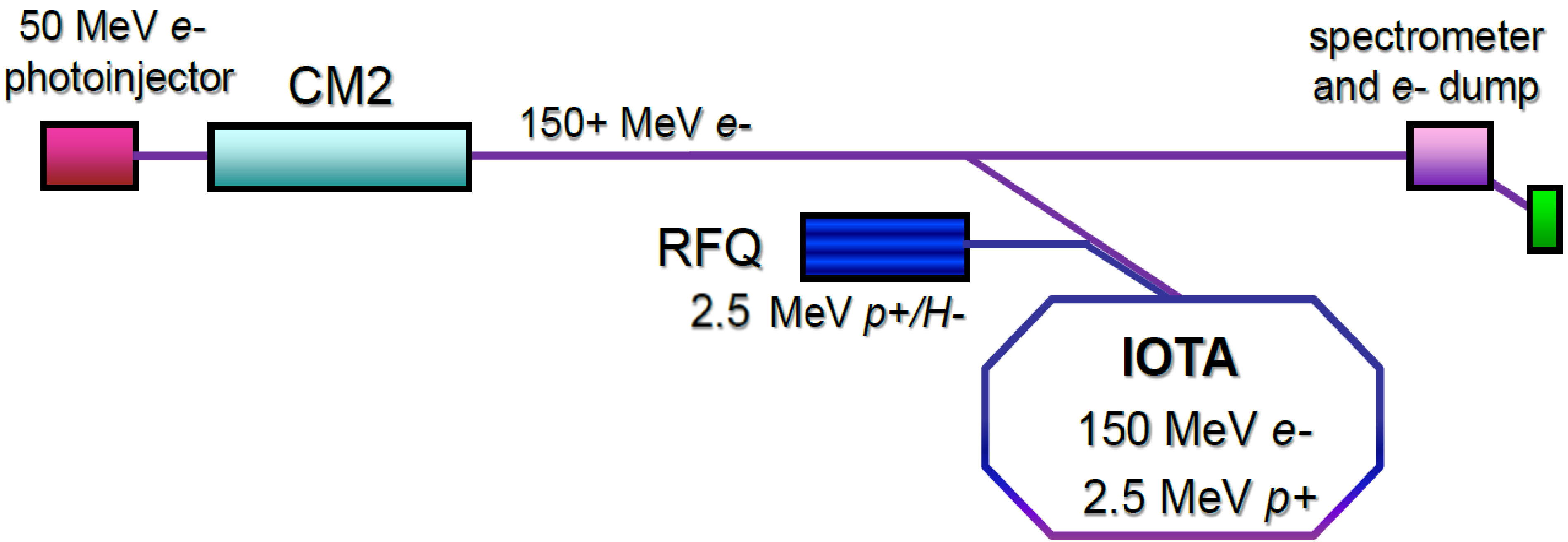
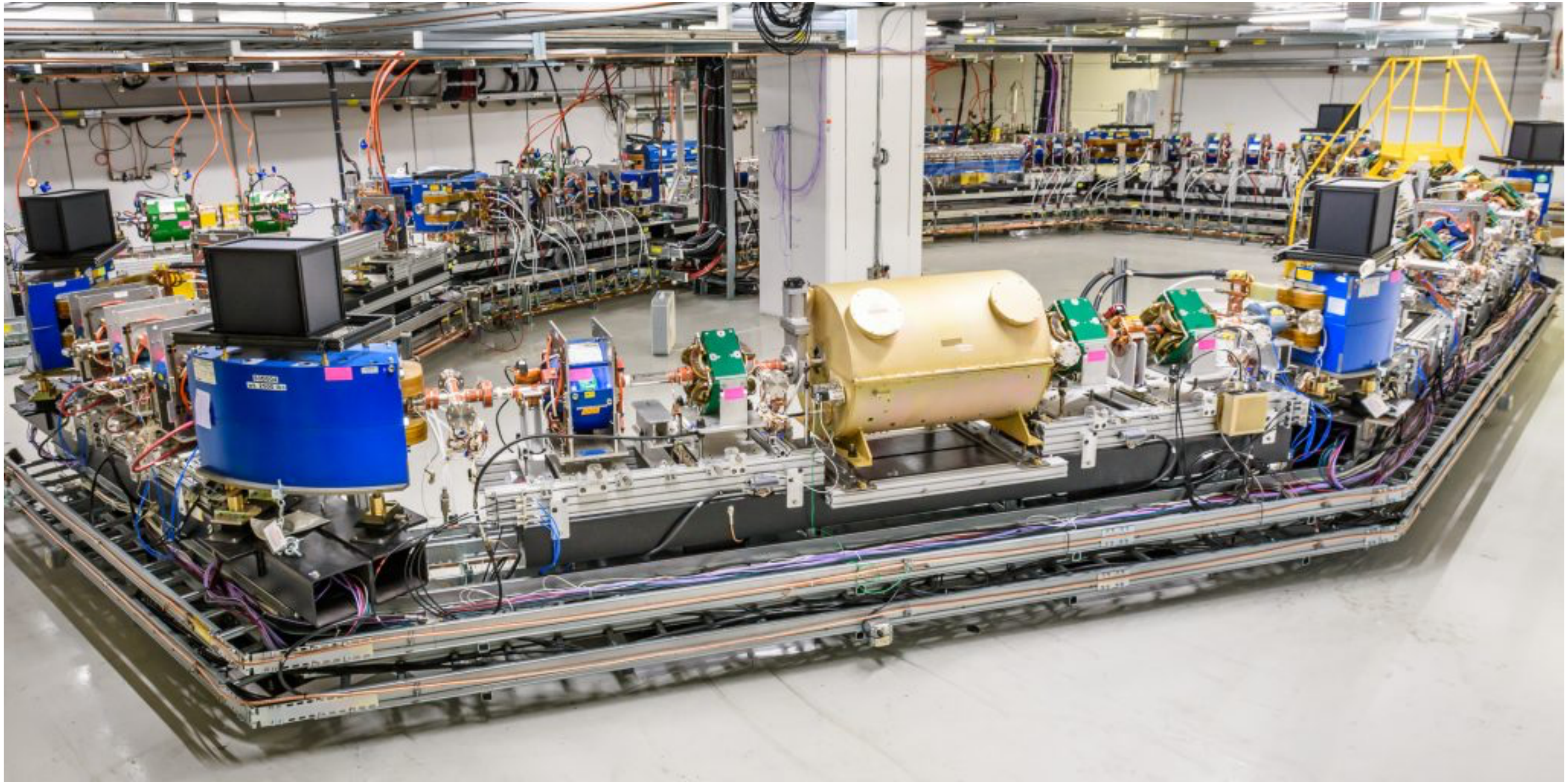
Fermilab Accelerator Science and Technology facility



IOTA Layout



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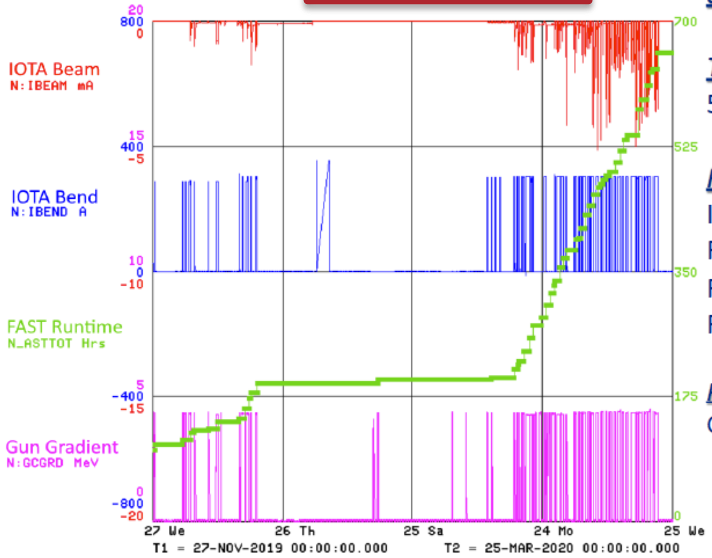
Operations through March 21 2020

Successful IOTA/FAST Run-2 Operations/Research

- **Started 11/27/19** – 3 weeks of commissioning after post-Run-1 upgrades
- 2 weeks planned shutdown for equipment installation
- 6 weeks Cryo system failure (APSTD)
- 5 weeks physics – **completed 3/21/20**



Thanks to Operations, all AD Support Departments

Total Run Time

557.9 Hrs

Reliable Machines

IOTA ring – no issues

FAST SRF linac – few hours of RF downtime recovered by RF support

Primary Downtime

Cryogenic Kinney Booster failure

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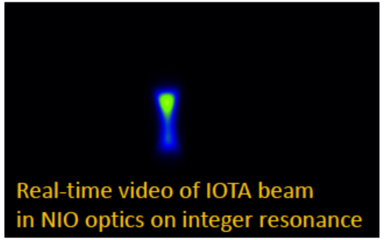
Operations through March 21 2020

IOTA/FAST Run-2 Research Highlights

IOTA Nonlinear Integrable Optics (NIO) experiments aim to develop technology for pushing beam intensity limits in synchrotrons

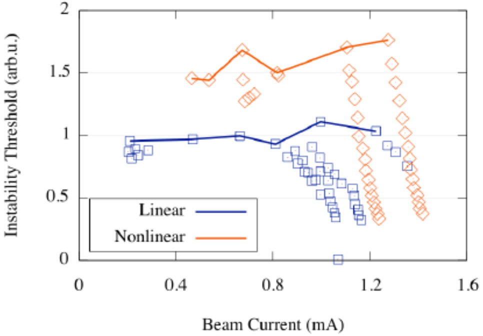
1. First demonstration of a practical implementation of the NIO concept in a real accelerator:

   In Run-2 showed stable nonlinear beam on integer resonance!



2. Demonstration of benefits of NIO lattices in high-intensity synchrotrons

   75% improvement of beam Instability threshold!



15 AD All Hands

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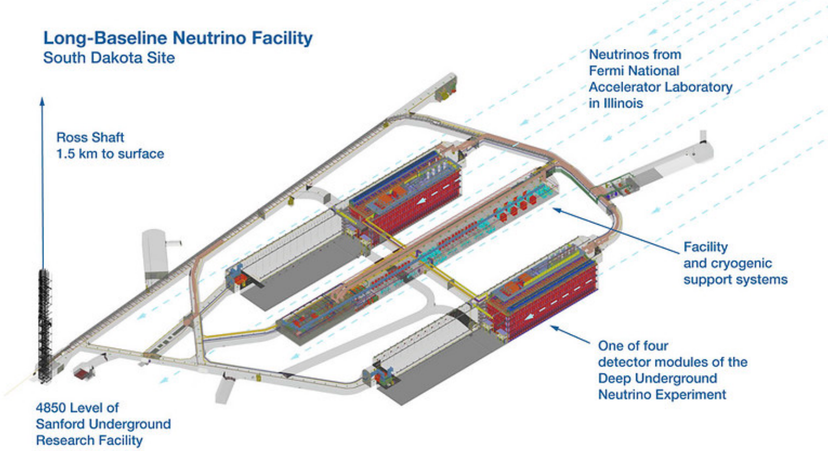
Key Questions beyond PIP-II

- Linac questions:
  - High energy H^- injection design!
  - Optimum cavity design?
  - Optimum klystron power distribution?
  - Industrialization and other cost-saving measures
  - Cost vs. pulse rate parameterization.
- RCS questions:
  - Injection energy?
    - do we need to increase the energy of the PIP-II linac beyond 800 MeV?
  - Circumference?
    - We've been assuming it's the same as the existing Booster, but might be better options.
  - Extraction energy?
    - Can we get above the 21 GeV transition energy of the Main Injector?
- Main Injector questions
  - What RF improvements will be necessary?
  - Can we adjust the lattice to lower transition energy?

Summary

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

- Neutrinos
  - NOvA @700+ kW
  - DUNE @ multi-MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities
  - 20 year project plans to minimize 40 year experimental plans
- Multi Stage Plan
  - PIP -> PIP-II -> Booster Upgrades
  - 700 kW -> 1.2 MW -> 2+ MW Long Baseline Program
  - Short Baseline and Muon Programs



Oldies and maybe goodies

Fermilab Program Goals

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

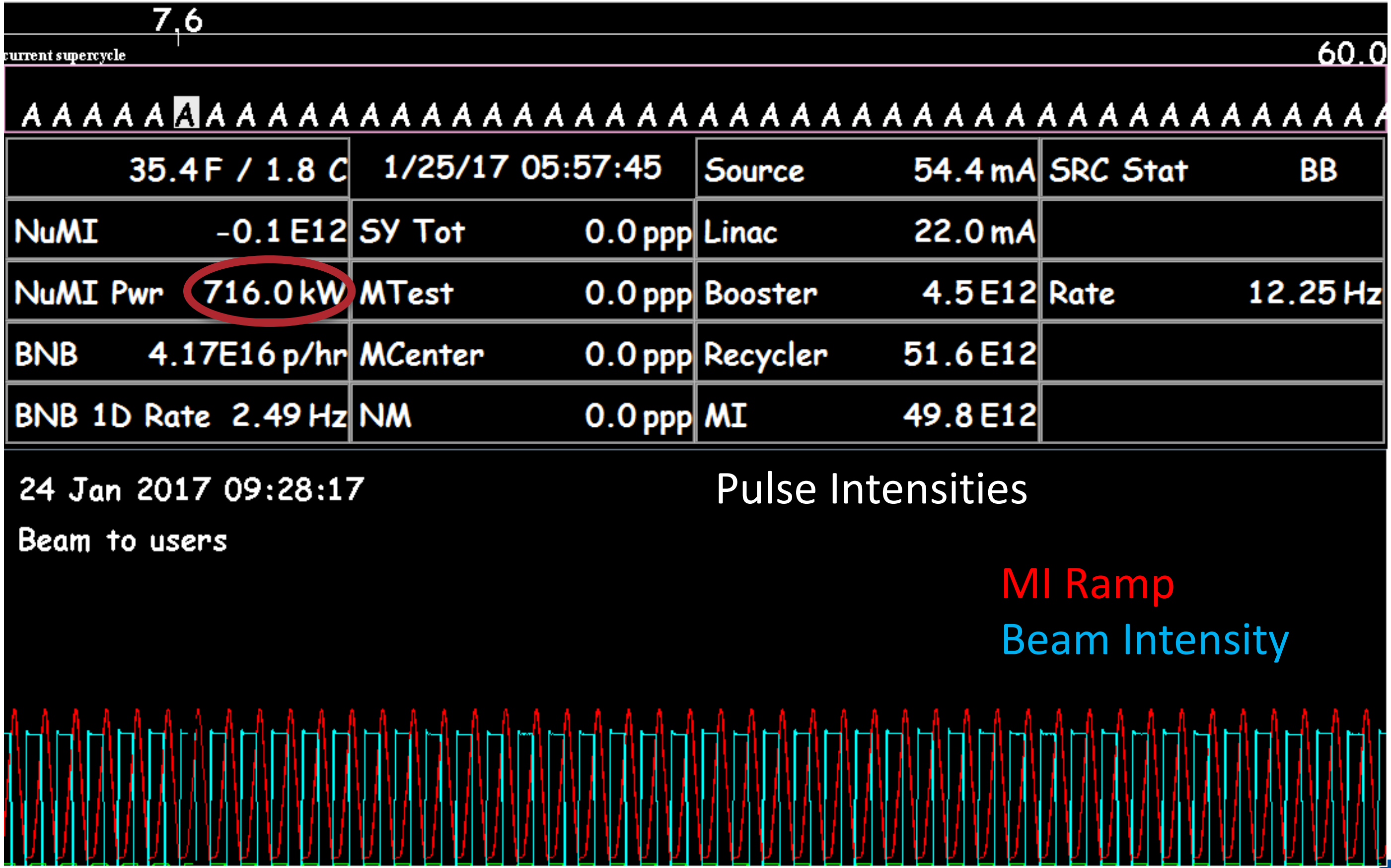
- Neutrinos
  - NuMI @700 kW
  - LBNF @ multi-MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities

⇒ ***This requires more protons!***

(and this statement tends to be time invariant)

"Upgrade the Fermilab Proton Accelerator Complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of > 1 MW by the time of the first operation of the new long-baseline neutrino facility" – Recommendation 14, P5 report

Current Performance



From DUNE CDR – May 2015 … Optimizations have lowered this time

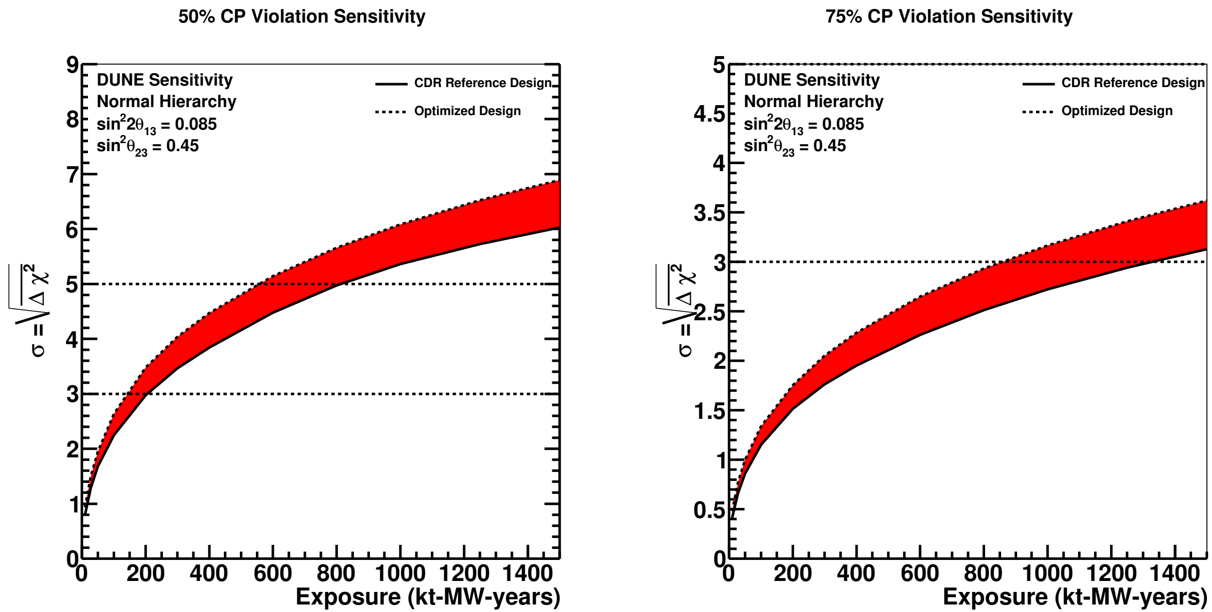


Figure 3.17: The significance with which CP violation can be determined for 50% (left) or 75% (right) of $\delta_{\rm CP}$ values as a function of exposure. The shaded region represents the range in sensitivity due to potential variations in the beam design. This plot assumes normal mass hierarchy.

DUNE Physics Goals

40kT with 700 kW is a 30+ year program

Detector Fiducial Mass (kton)	Proton Beam Power (MW)	YEARS to reach 120kT.MW.yr	YEARS to reach 600kT.MW.yr	YEARS to reach 900kT.MW.yr
10	0.7	17	86	129
20	0.7	9	43	64
30	0.7	6	29	43
40	0.7	4	21	32
10	1.2	10	50	75
20	1.2	5	25	38
40	1.2	3	13	19
20	2.4	3	13	19
40	2.4	1	6	9

1 MW year ~ 1e21 protons at 120 GeV

DUNE Physics Goals

40kT with 2.4 MW is a 10 year program

Detector Fiducial Mass (kton)	Proton Beam Power (MW)	YEARS to reach 120kT.MW.yr	YEARS to reach 600kT.MW.yr	YEARS to reach 900kT.MW.yr
10	0.7	17	86	129
20	0.7	9	43	64
30	0.7	6	29	43
40	0.7	4	21	32
10	1.2	10	50	75
20	1.2	5	25	38
40	1.2	3	13	19
20	2.4	3	13	19
40	2.4	1	6	9

1 MW year ~ 1.1e21 protons at 120 GeV

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DUNE Physics Goals

40kT with 1.2 MW is a 20 year program

Detector Fiducial Mass (kton)	Proton Beam Power (MW)	YEARS to reach 120kT.MW.yr	YEARS to reach 600kT.MW.yr	YEARS to reach 900kT.MW.yr
10	0.7	17	86	129
20	0.7	9	43	64
30	0.7	6	29	43
40	0.7	4	21	32
10	1.2	10	50	75
20	1.2	5	25	38
40	1.2	3	13	19
20	2.4	3	13	19
40	2.4	1	6	9

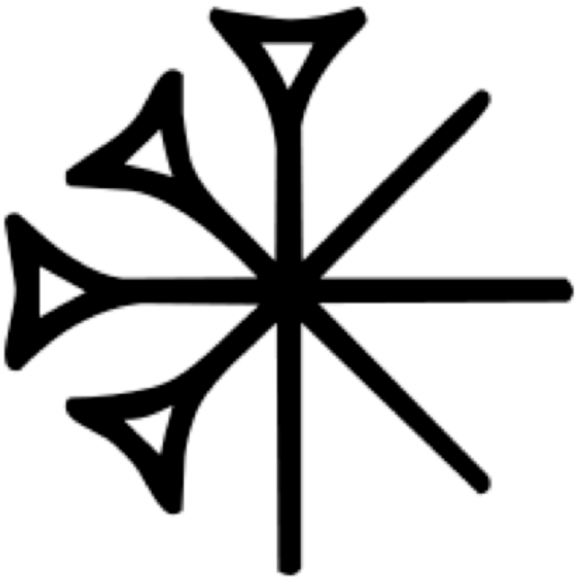
1 MW year ~ 1.1e21 protons at 120 GeV : E1A 0.0002e21

"P5 Report"

- The Particle Physics Project Prioritization Panel (P5) advises the US Department of Energy (DOE) Office of High Energy Physics on research funding priorities in high energy physics
- After a lengthy process, the panel released a report in May, 2014. Top priorities for Fermilab:
  - Support the LHC and its planned luminosity upgrades
  - Pursue the g-2 and Mu2e muon programs*
  - Focus on a high energy neutrino program to determine the mass hierarchy and measure CP violation.
    - "Flagship" activity
    - Will ultimately require a "multi-megawatt" beam at 60-120 GeV
  - Continue at least R&D toward a future linear e^+e^- collider (ILC)

Context of ANU

- In Sumerian mythology and later for Assyrians and Babylonians, Anu (also An; (from Sumerian *An □ = sky, heaven)) was a sky-god, the god of heaven, lord of constellations, king of gods, spirits and demons, and dwelt in the highest heavenly regions. It was believed that he had the power to judge those who had committed crimes, and that he had created the stars as soldiers to destroy the wicked.



Sumerian cuneiform for ANU

Experimental Program

- At 8 GeV
  - Neutrinos (Booster) – single pulse extraction
    - ANNIE
    - MicroBooNE
    - ICARUS (future)
    - SBND (future)
  - Muons (Recycler & Muon Rings)
    - g-2 – single pulse extraction
    - Mu2e (future) – slow extraction

- At 120 GeV
  - Neutrinos – single pulse extraction
    - MINOS+
    - MINERvA
    - NOvA
    - DUNE (future)
  - Fixed Target – slow extraction
    - SeaQuest
    - Test Beam Facility

STATISTICS in Neutrino Experiments

Neutrino Events/Unit Time =

Neutrino Flux x ← **BEAM = Protons/year + Target/horns, Beam Energy**

Neutrino Cross-section/Nucleon x ← PHYSICS!

Number of Nucleons ← **Detector = Mass + Efficiency**

Neutrino Experiments Need : Mass * Power * Time

We want to achieve our physics goals in a timely manner!

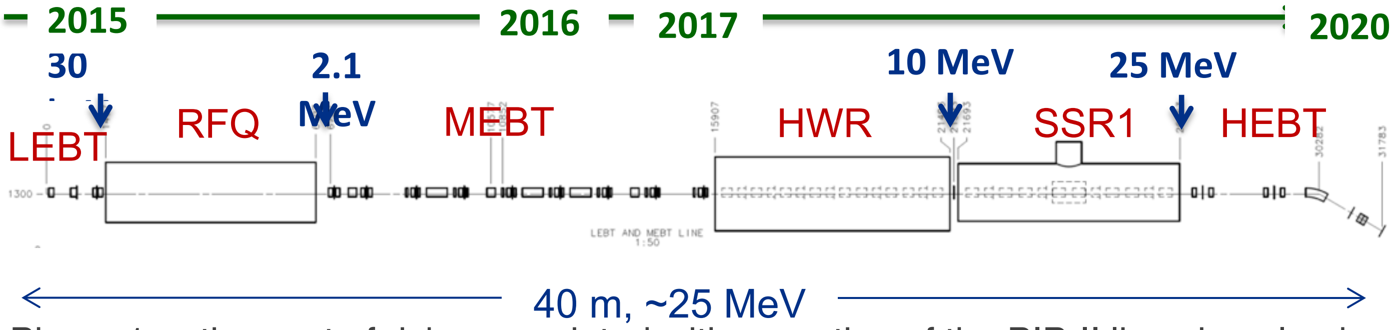
PIP-II

- Formal Department of Energy Project in the Office of High Energy Physics
  - Critical Decision 0: Mission Need Statement
    - Office of Science Approval October 2015
    - Energy Systems Acquisitions Advisory Board November 2015
  - Critical Decision 1: Approve Alternative Selection and Cost Range
    - Energy Systems Acquisitions Advisory Board July 2018
  - Critical Decision 2: Approve Performance Baseline
    - DOE : IPR January 2020 and ICR February 2020

  - Vigorous R&D program to address technical, cost, and schedule risk underway

  - Anticipate construction start early in next decade, with completion in 2026-2027 time frame

Building up the first 25 MeV : PIP-II Injector Test



Phase 1: retirement of risks associated with operation of the PIP-II linac in pulsed mode as required for neutrino operations and described in the CDR (1% duty factor). The primary risks to be retired during this period (now-2020) include:

- Achievement of required beam characteristics from the ion source through the SSR1 cryomodule
- Demonstration of MEBT chopper operations at a level required for Booster injection
- Demonstration of the operation of the HWR cryomodule, with beam, in close proximity to the MEBT beam absorber
- Demonstration of stable beam acceleration in the SSR1 cryomodule, under the full control of prototype RF control systems, including resonance control within the cavities

Beyond PIP-II

- By the time PIP-II is realized, the Booster will be more than a half century old, and it's unrealistic to believe that it can be pushed further, in terms of performance:
  - No beam pipe in magnets! ➔ troublesome impedances from magnet laminations.
  - Presently the decelerating voltage (from impedance) at transition is above 100 kV/turn
    - Transition crossing with more than 50% intensity increase looks impossible without reducing impedance
    - No realistic way to do this.
- Further increases in power will require replacing the Booster. Options are:
  - A pulsed linac to go from the PIP-II linac to 8 GeV
  - Some sort of Rapid Cycling Synchrotron (RCS)
    - Possibly increase the energy of the linac to 2 or 3 GeV?
- Replacing the Booster is critical to going beyond PIP-II intensities.

Integrable Optics Test Accelerator

- **Unique features**:
  - Can operate with either electrons or protons (up to 150 MeV/c momentum)
  - Large aperture
  - Significant flexibility of the lattice
  - Precise control of the optics quality and stability
  - Set up for very high intensity operation (with protons)
- **Based on conventional technology** (magnets, RF)
- **Cost-effective solution**
  - Balance between low energy (low cost) and research potential

S. Antipov et al., arXiv:1612.06289 December 2016